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LOUISVILLE DISTRICT / HUNTINGTON DISTRICT

Ohio River Mainstem Systems Study (ORMSS)

Interim Feasibility Report:
J.T. Myers and Greenup Locks Improvements

INDIANA, KENTUCKY and OHIO

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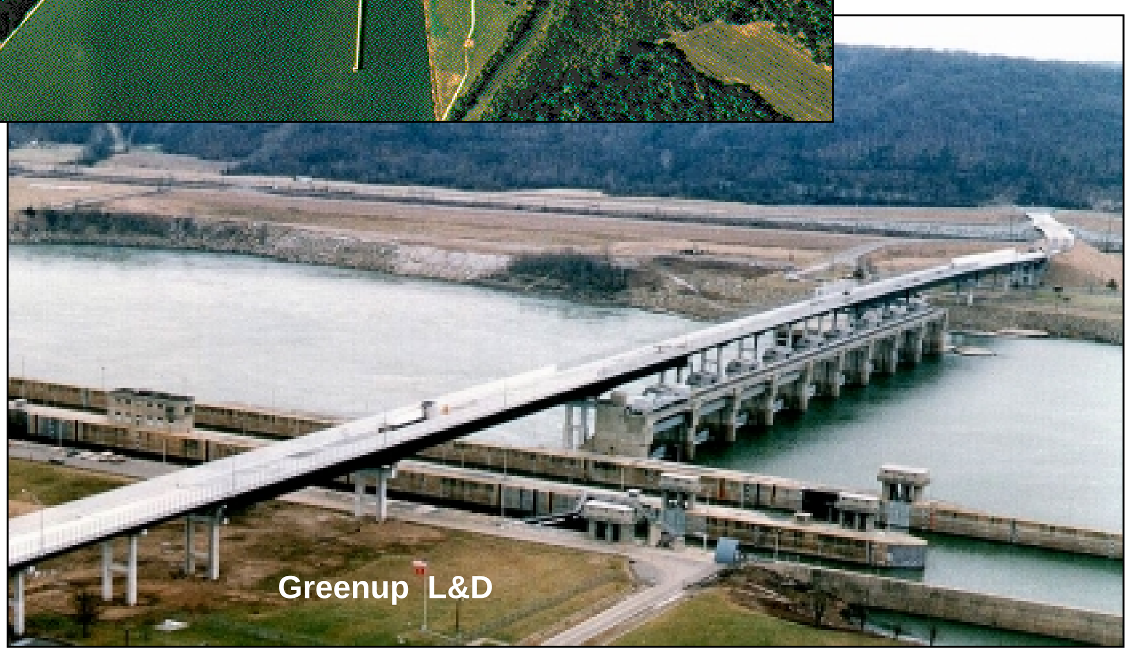

April 2000

DEPARTMENT OF THE ARMY
U.S. ARMY ENGINEER DISTRICT, LOUISVILLE
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Overall Report Structure

Document Code	Title	
MR	Main Report and EIS	
ERD	Environmental Reference Data	
EC	Economics Appendix	
RE	Real Estate Appendix	
GE	**General Engineering Reference Data**	**THIS DOCUMENT**
ED-1	J.T.Myers Engineering Site Appendix	
ED-2	Greenup Engineering Site Appendix	

SECTION 1

INTRODUCTION

1.1 PURPOSE OF THIS APPENDIX

- To provide technical or detailed aspects of Plan Formulation that are not covered in the Main Report.
- To provide Engineering regional (non-lock specific) data.
- To provide data pertinent to BOTH the Myers and Greenup sites – whereas lock-specific design data are contained in Documents ED-1 and ED-2.
- To provide general engineering criteria and background data pertinent to the study.

1.2 PRIOR STUDIES AND REPORTS

In Fiscal Years 1990-91, funds were appropriated for an Interim Reconnaissance Report for Uniontown Lock and Dam (now J.T.Myers L&D). Myers Lock is located in the lower reaches of the Ohio River, about 30 miles downstream of Evansville, Indiana -- just upstream of the mouth of the Wabash River. The Uniontown Recon focused on only this one lock site, and in June 1991 a Recon Report was issued, which found positive benefits for traffic-capacity expansion at the Uniontown site. Corps Headquarters' review of this Reconnaissance Report, dated 14 February 92, stated:

> The Corps must take a "systems look" to properly address the level of investments needed to continue to provide a viable navigation system ***on the Ohio River Mainstem***. ... the entire Ohio River Mainstem navigation system should be carefully reviewed, but your primary emphasis for this study should concentrate on the lower portion of the river.

The following table summarizes documents pertinent to the Ohio River Mainstem Study, particularly those relevant to J.T.Myers and Greenup Locks and Dams. This list includes both Authorization and Technical (in-house) Documents. In the actual Interim Report, only a few significant final Authorization or management documents will be listed in the Main Report. The other (technical) documents will be listed in a similar table in the Plan Formulation Appendix—in order to provide documentation of the formulation/design process.

TABLE 1-1. LIST OF PRIOR STUDIES / REPORTS pertinent to the ORMSS MYERS/GREENUP INTERIM REPORT

Document Title	Date	Produced by	Summary	Conference or Reference	Disposition / Status
Information Brochure for Periodic Inspection, Uniontown L&D	Jun-74	CELRL-ED	Reference data used for periodic inspections of the L&D facilities.	not applicable	Includes "as-built" drawings for Uniontown L&D (now Myers L&D). Constructed June 1965- Sept 1972.
Final Technical Report H-75-6 Navigation Conditions at Cannelton L&D, Ohio River	Apr-75	CEWES-HS	Pre-construction hydraulics model investigation for Cannelton L&D -- replaced old L&D's 43-45 w/1-1200 ft lock & 1-600 ft lock + 1365 ft of gated, non-navigable dam	not applicable	Uniontown L&D is 1 of 5 new L&D's (circa 1965) to replace 11 old navigation structures on the Ohio R.
Final Technical Report H-75-9 Navigation Conditions at Uniontown L&D, Ohio River	May-75	CEWES-HS	Pre-construction hydraulics model investigation for Uniontown L&D -- replaced old L&D's w/1-1200 ft lock & 1-600 ft lock + gated spillway and fixed overflow dam	not applicable	
Ohio River Mainstem Nav Study Interim Reconnaissance Study Uniontown Locks & Dam	1-Jun-91	CELRL-PDF	B/C for third 1200' chamber = 1.5. B/C for 600' chambr extension = 0.8.	Recon Review Conference., Louisville 17 Sept 91	CECW-PE review memo of 14 Feb 92. Recon eventully certified per acceptance of P.S.P. in June 96.
Uniontown / ORMS LowCapitalCost Lock Alternatives (DACW27-92-D-0010)	29-Jan-93	HARZA Engrs, (Chicago, IL) for CELRL-ED-DS	Discussed alternatives for different lock components: 6 different walls, 6 gates, 5 empty-fill systems.	Plan Formulation / ED-D coordination. 1st step in low-cost alternatives' design.	Led to later delivery orders by HARZA for layouts at Uniontwn, Newburgh, Cannelton.
Uniontown Locks & Dam/ Ohio River Mainstem Study Initial Project Mgt Plan (IPMP)	1-May-93	CELRL-PDF	Outlined a $10M study, focusing on Uniontn, Newbrgh, & Cannltn Lks, to be complete in 1997.	CECW-P / ORD staffs meet, 10Dec93. IPMP apprvd 7Jun93 by ORL Proj. Mgt. Board.	CECW-PD draft review memo of 6 Jan 94, called for broader scope, includg: (1) itemize all Mainstem nav.costs (long-term); (2) detailed Risk assessmt.
ORMSS Design & Cost Screening of Lock Expansion Alternatives - Uniontown L&D (Final Report)	Jan-95	HARZA Engrs, (Chicago, IL) for CELRL-ED-DS	Evaluated low-cost lock expansion alternatives (including extending the 600-ft lock + low-cost methods to construct a new 1200-ft lock)	Final submittal, Delivery Order 0002, DACAW27-92-D-0010	Led to alternatives per later INCA contract.
Ohio River Mainstem Systems Study, Project Study Plan (PSP) [submittal # 1]	16-Jun-95	CELRD-wide team, edited: CELRL-PDF	Outlined $48M study of entire Main Stem, complete in 2002. Assumes full Feasibility detail for 9 sites.	ORD / CECW staffs, Aug95. Briefed Dir CW, Sep95. Certified 16Jun95, by ORD team leaders & Commanders.	CECW memo 13 Oct 95
ORMSS Design & Cost Screening of Lock Expansion Alternatives - Cannelton L&D (Final Report)	July-95	HARZA Engrs, (Chicago, IL) for CELRL-ED-DS	Evaluated low-cost lock expansion alternatives (including extending the 600-ft lock + a low-cost method to construct a new 1200-ft lock)	Final submittal, Delivery Order 0003, DACAW27-92-D-0010	Led to alternatives per later INCA contract.

TABLE 1-1. LIST OF PRIOR STUDIES / REPORTS, ORMSS (continued)

Document Title	Date	Produced by	Summary	Conference or Reference	Disposition / Status
ORMSS Design & Cost Screening of Lock Expansion Alternatives - Uniontown L&D (Final Report)	July-95	HARZA Engrs, (Chicago, IL) for CELRL-ED-DS	Evaluated low-cost lock expansion alternatives (including extending the 600-ft lock + a low-cost method to construct a new 1200-ft lock)	Final submittal, Delivery Order 0004, DACAW27-92-D-0010	' '
ORMSS DRAFT Project Study Plan (PSP) [submittal # 2]	1-Feb-96	CELRD-wide team, edited: CELRL-PDF	Outlines $37M study, to be complete in 2000. Costs assume full Feasibility-detail at equivalent of 5 sites.	Fig.4-1 and study outline per discussion w/ CECW-P, 12Dec95 at LexingtonKY	More detail / organization: specific tasks and goals clearly shown. Differentiation between "early action" and other study efforts.
Revised June 96 Project Study Plan (PSP) [submittal # 3]	1-Jun-96	CELRL-PDF	Similar to Feb 96 PSP in terms of overall schedule and costs, but with "Lower River" early actions removed.	CEORD memo to Dir. of Civil Works, HQUSACE, 10Apr96	Lower River "early-action" initiatives removed-- new innovative designs allow "in-water" construction with minimized traffic delays.
ORMSS Workshop Documentation, March 18-22 1996, DACW27-95-C-0126	11-Jun-96	INCA Engineers (Bellevue, WA) for CELRL-ED-DS	Results of week-long workshop. Includes PRELIM costs for various lock components.	ORMSS engineers' workshop, Bellevue, 18-22 Mar 96	"Jumpstart" to INCA-Corps collaboration on ORMSS designs
Ohio R. Navigation System Report, 1996 COMMERCE ON THE OHIO RIVER AND TRIBUTARIES	1996	CELRH-NC	The Biennial Report of Commerce and a system-wide inventory of facilities on the Ohio River and its tributaries	not applicable	This color., 20+ page brochure is updated every 2-3 years, with an annual stats update other years.
ORMSS Design Presentation for the 600 C-1 600-ft Lock Extension Alternative (DACW27-95-C-0126)	Mar-98	INCA Engineers (Bellevue, WA) for CELRL-ED-DS	Handout for presentation of to team engineers -- nine different empty-fill configurations	Document prepared for presentation to the ORMSS design/formulation teams at CELRL on 10-11 March 1998.	Handout for presentation of to team engineers -- nine different empty-fill configurations
ORMSS Workshop Documentation, Supp. #1: Alternative 600C Report August 29, 1996, DACW27-95-C-0126	Aug-96	INCA Engineers (Bellevue, WA) for CELRL-ED-DS	Plan 600C utilizes various elements: Float-in gate bay and lock wall monoliths, split lateral fill/empty system with outlet diffuser, floating approach walls	Supplement to workshop documentation for an additional Plan 600-C, developed following the workshop of Mar 96	
ORMSS Workshop Documentation, Supp #2: Alternative 600D Report September 27, 1996, DACW27-95-C-0126	Sep-96	INCA Engineers (Bellevue, WA) for CELRL-ED-DS	Plan 600D utilizes various elements: Float-in gate bay and lock wall monoliths, split lateral fill/empty system with outlet diffuser, floating approach walls	Workshop documentation for an additional alternative, 600-D, developed following the workshop of Mar 96	
ORMSS Alternative 600C Adaptation Report October 29, 1996	Oct-96	INCA Engineers (Bellevue, WA) for CELRL-ED-DS	Prelim. effort to adapt Alt 600-C for the Markland, Cannelton & Newburgh L&D sites -- site differences & costs.	not applicable	Useful for final ORMSS report -- Plan 3 adaptions to various sits

TABLE 1-1. LIST OF PRIOR STUDIES / REPORTS, ORMSS (continued)

Document Title	Date	Produced by	Summary	Conference or Reference	Disposition / Status
Lock Closure Data Base for Louisville, Huntington & Pittsburgh Districts ***(Final Report, DACW69--93-D-0017, W.O. 004)***	Apr-96	Jack Faucett Associates, Bethesda, MD., for CELRH-NC	Inventoried high-lift lock closures in the Ohio R. system exceeding 8 hrs duration, from 3 different sources of data, w/ statistical analysis, for O&M analyses.	Various Econ/Plan Formulation team members	partial input to Without-Project lock closures' assumptions
Report - ORMSS Prepare Conceptual Design for Emsworth L&D, Ohio R, 100% submittal ***(DACW57-D-0003, Del.O.# DV01)***	Sep-97	INCA Engineers (Bellevue, WA) for CELRP-ED	Explains engr'g drawings (below) for concept level design for adding a 1200' lock at Emsworth L&D, Ohio R.	Various team and Oversight meetings -- first step towards upper Ohio L&D improvement costing.	Useful for final ORMSS report -- Emsworth is one of three old L&D facilities on the upper Ohio River.
Drawings - ORMSS Prepare Conceptual Design for Emsworth L&D, Ohio River, 100% submittal ***(DACW57-D-0003, Del.O.#DV01)***	Sep-97	INCA Engineers (Bellevue, WA) for CELRP-ED	Drawings detail engr'g and concept level design for adding a 1200-ft lock at Emsworth L&D, Ohio R. (See companion report)	' '	' '
Report - ORMSS Prepare Conceptual Design for Montgomery L&D, Ohio River, 100% submittal ***(DACW57-D-0003, Del.O.# DV03)***	Aug-97	INCA Engineers (Bellevue, WA) for CELRP-ED	Document details engr'g drawings for concept level design for adding a second 600-ft or a 1200-ft lock at Montgomery L&D, Ohio R.	' '	Useful for final ORMSS report -- Montgomery is one of 3 old L&D facilities on the upper Ohio River.
Drawings - ORMSS Prepare Conceptual Design for Montgomery L&D, Ohio River, 100% submittal ***(DACW57-D-0003, Del.O.#DV03)***	Sep-97	INCA Engineers (Bellevue, WA) for CELRP-ED	Document details engr'g drawings for concept level design for adding a second 600-ft or a 1200-ft lock at Montgomery L&D, Ohio R.	' '	' '
Report - ORMSS Prepare Conceptual Design of Dashields L&D, Ohio River, 100% submittal ***(DACW57-D-0003, Del.O.#DV03)***	Sep-97	INCA Engineers (Bellevue, WA) for CELRP-ED	Document details engr'g drawings for concept level design for adding a second 600-ft or a 1200-ft lock at Dashields L&D, Ohio R.	' '	Useful for final ORMSS report -- Dashields is one of 3 old L&D facilities on the upper Ohio River.
ORMSS Field Inspection Report of all L&D Facilities on the Ohio River (Pittsburgh, Huntington & Louisville Districts)	1996-1997	CELRP-EDD**;** inspections by a core group of LRP/ LRH/ LRL engineers.	Details visual inspection of facilities at each L&D plus interviews with Lockmasters & projects' O&M Leaders. Provides numerical ratings for various L&D components, and photos of conditions at each L&D.	Various team and Oversight meetings -- comparative data to begin reliability analyses.	A step in the process of evaluating risk & reliability for the L&D components and facilities throughout the Ohio R. Mainstem system.
OHIO RIVER NAVIGATION SYSTEM -- 1997 Statistical Supplement	1997	CELRH-NC	Intervening-year statistical update to the biennial Ohio R. Nav. System Report (1996)	The publication also references other Waterway Data Publications and their sources as well as a World Wide Web data access site.	Color., 20+ page Nav.Center brochure (see 1996 report listing above)
ORMSS Design Presentation for the 600 C-1 600-ft Lock Extension Alternative ***(DACW27-95-C-0126)***	Mar-98	INCA Engineers (Bellevue, WA) for CELRL-ED-DS	An advanced presentation to team of 9 different empty-fill configurations (per next document below).	Document prepared for presentation to the ORMSS design/formulation teams at CELRL on 10-11 March 1998.	Discussions led to minor revisions in next document (below).

TABLE 1-1. LIST OF PRIOR STUDIES / REPORTS, ORMSS (end)

Document Title	Date	Produced by	Summary	Conference or Reference	Disposition / Status
ORMSS - 100% Submittal Constructibility and Cost Estimate (Analyses) for Prototype Alts. ***(DACW27-95-C-0126)***	May-98	INCA Engineers (Bellevue, WA) for CELRL-ED	Descriptions, drawings, constructn schedules, & cost estimates for 9 configuratns of F/E systems. Constructibility evaluations.	Report requested by Plan Formulation and ED teams, and incorporates comments received from 10-11 March and District reviews.	Essentially, evaluated sensitivity of layout costs to various empty-fill configuration for both 600 Aux. Extensions, and 3rd lock plans.
ORMSS -Engineering Appendix for Large-Scale Improvements (Prototype Designs) , ***DACW 27-95-C-0126***	Jun-98	INCA Engineers (Bellevue, WA) for CELRL-ED	Feasibility-level design (50% complete) based on J.T.Myers site, considered site adaptable to other Main Stem sites	INCA contract requirement: 50% point submittal	on-going development of Myers Engineering Technical Appendix for Interim Report
MANAGEMENT SUMMARY -- Cultural Resources Database Construction for ORMSS ***(DACA27-960C-0077)***	Aug-98	Gray & Pape, Cultural Resources Consultants, Richmond, VA for CELRL-PD-E	Summarizes efforts in creating 6 cultural resource database files for portions of 6 states along the Ohio R. mainstem nav. system (PA, WV, OH, KY, IN and IL), and tabulates findings.	Cultural Resources inventories for ORMSS.	Designed to work in coordination with a GIS database established by Gulf Engineers/Consultants (GEC)
REPORTS SPECIFIC to GREENUP LOCKS and DAM					
Greenup Locks and Dam, Ohio River, Design Memo #1, Huntington District, Corps of Engineers	Dec-53	CELRH-ED	General Design Memorandum -- overall layout and design assumptions	NA	Beginning of Post-Authorization design work
Navigation Conditions at Greenup Locks and Dam, Ohio River, Hydraulic Model Investigations, Technical Report #2-469	Jan-58	CEWES-HS for CELRH-ED			
Filling and Emptying System for Greenup and Markland Locks, Ohio River, Hydraulic Model Investigations, University of Minnesota	Jan-62	Univ. of Minnesota Hydraulics Lab for CELRH-ED			
Greenup Locks and Dam Periodic Inspection Report #1	Oct-68	CELRH-EC-DS	Reference data used for periodic inspections of the L&D facilities		Includes "as-built" drawings for Greenup L&D, constructed from 1955 to 1962
Meldahl L&D 600-ft Lock Extension Plan, Recon.Level Screening Study, Final submittal, ***DACW69-97-D-0012, D.O.# 0001***	Mar-98	Black & Veatch (Kansas City, MO) for CELRH-EC-DC	Evaluated low-cost lock expansion alternatives		Initial first look at alternatives and cost for a Meldahl 600-ft Lock Extension

SECTION 2

OHIO RIVER NAVIGATION SYSTEM HISTORY AND STATUS OF IMPROVEMENTS

2.1 HISTORY

2.1.1 Early Settlers and Steamboat Era

The first European explorers to visit the Ohio River Valley are believed to have arrived with De Soto's expedition in 1540. The first pioneers consisted of trappers, fur traders, and soldiers. Canoes provided the most common mode of transportation on the rivers. Over time, the French came to dominate the area with fur trading as their primary economic interest. The increased presence of Euro-American colonial traders by the mid eighteenth century prompted the French to build forts on the Allegheny River in an attempt to reclaim the Ohio River Valley. In 1753, Virginia militiamen, led by Major George Washington, attempted to construct a fort where the Allegheny and Monongahela Rivers combine to form the Ohio River. The French drove them away and built Fort Duquesne instead. In 1758, British forces regained control of the area and replaced Fort Duquesne with Fort Pitt. With the establishment of Fort Pitt, the City of Pittsburgh evolved in the surrounding areas. Because of its strategic location at the head of the Ohio River, Pittsburgh became a major port of embarkation for settlers and commodities traveling west. Flatboats and barges carried the trade of the country downstream. Since flatboats and barges could only travel downstream, the lumber making up these vessels was frequently sold at destination. Keelboats provided the first means for travel both upstream and downstream on the river. They provided regular passenger and freight service between Pittsburgh, Cincinnati, and Louisville. It typically took one month to complete the round trip between Pittsburgh and Cincinnati.

The steamboat era on the Ohio River began in 1811 when the New Orleans departed from Pittsburgh. Early steamboats had deep keels and were not suited for navigation on the shallow western rivers. The development of the first shallow draft steamboat in 1816 set a pattern for the river steamboats which followed. The presence of snags and sandbars, however, plagued navigation. Deadly snags could easily hole out and sink a steamboat without warning. Accidents and fatalities were commonplace. The success of the steamboat and its impact throughout the

Ohio River Basin led to the first significant action by the Federal Government to improve navigation conditions.

2.1.2 Improvements to Navigation

When compared to overland routes, the Ohio River provided an easy mode of travel to the west. Travel on the river, however, had its fair share of hazards. In its original condition, the Ohio River was obstructed throughout its entire length by snags, rocks, and sand bars. Navigation was difficult and hazardous due to extreme variations in channel width and depth. During periods of low water, the depth could be as little as one foot over the worst shoals. This did not provided sufficient depth for vessels to safely navigate the river.

On 24 May 1824, the first Inland Waterways Improvement Act directed that experiments be conducted to determine the best method for dealing with the sandbars and snags that continued to obstruct navigation on the Ohio River. At this time, the primary function of the Army Engineers in the Ohio River Basin was to improve and develop waterway navigation for steamboat commerce.

One of the first obstacles to be addressed was the rapids near Louisville known as the "Falls of the Ohio". The rapids dropped nearly 26 feet and extended for two miles. Navigation over the falls was impossible except during periods of high water. The Louisville and Portland Canal was completed in 1830 allowing river traffic to bypass the falls. The canal was 1.9 miles long and had three successive locks measuring 50 feet by 185 feet. Since completion of the canal, continuous improvements have been made to the project, which is now known as McAlpine Locks and Dam.

The development of the double-hulled snagboat by Captain Shreve greatly reduced the snag hazard. Snags were large and numerous with some weighing over one hundred tons. Removal of rock in the channel near Grand Chain (an area of rocky river-bottom near the existing L&D 53) commenced in 1830. The use of cutoff dams on back channels and wing dikes to concentrate flow in the main channel improved the navigable depth in most areas to a minimum channel depth of three feet. In 1825, the first wing dike was built at Henderson Bar. Dikes were constructed at Scuffletown and Sisters Islands in 1831 and at French and Cumberland Islands in 1832. Improvements upstream of Louisville were limited to snag removal until 1836 when the dams at Brown Island were built. The success of this project led to the construction of many wing dikes and back channel dams between Pittsburgh and Cincinnati. Improvements to navigation continued on a regular basis through 1844. Wavering political leadership and the Civil War essentially ended all work from 1845 to 1866.

2.1.3 Canalization

In 1835, Lieutenant George Dutton first expressed his view that the construction of locks and dams was necessary to provide adequate navigation conditions for year round use of the Ohio River. The idea was overlooked at first due to the magnitude of the engineering problems to be dealt with and objections of the river users who believed that dams would be a hindrance to navigation. This attitude began to change during the mid nineteenth century when one way flatboats used to transport coal to downstream destination points were gradually replaced by steamboats towing fleets of coal barges downriver and returning with the empty barges for reuse. It soon became apparent that a system of locks and dams was needed to accommodate the growing coal fleets. Major W. E. Merrill proposed construction of thirteen locks and movable dams between Pittsburgh and Wheeling in 1874. The proposed system was an essential part of the plan to provide a 6-foot navigable depth on the upper Ohio River.

The concept of a movable dam was adopted to meet the needs of coalboat operators. The dam could be raised during low flows to maintain a harbor pool and lowered during high water to allow passage of the coalboat fleets without lockage. The movable wicket dam invented in 1852 by Chief Jacques Chanoine of the French Corps of Engineers was adapted to meet the needs of the Ohio River. The wickets consisted of a set of timbers that were bolted together. During high water they lay flat against a masonry foundation leaving an open channel for navigation. At low water, the wickets were raised on end to form a dam.

The River and Harbor Act of 1875 provided funds for the construction of a movable dam 4.7 miles downstream of Pittsburgh at Davis Island. The original goal of the project was to provide a pool at Pittsburgh for assembling of coalboats and formation of tows suitable for the downstream run when a “coalboat rise” occurred on the river. Work began in 1877 and the structure was opened to traffic on 7 October 1885. Since it was the first canalization project on the Ohio River, the Davis Island Dam became known as Dam 1.

The Davis Island Dam was 1223 feet long with a chanoine wicket pass of 559 feet and three chanoine weir sections. The back channel of the Ohio River was closed with a non-navigable stone-filled timber-crib dam. Because of ice conditions typically experienced on the Ohio River, the wickets in the navigable pass were raised and lowered with a maneuverboat. A service bridge was used to raise and lower the weir wickets. Damage to the bridge by barges and debris led to the use of a maneuverboat for raising and lowering all of the wickets. A drift gap was also added in 1889 to pass floating logs and other debris. Fortunately, the difficult task of raising and lowering the wickets occurred at infrequent intervals during very low or high water.

The 110 foot wide by 600 foot long lock at Davis Island was designed to meet the needs of the coalboat fleets. These dimensions became standard for the initial canalization of the entire Ohio River. The lock chamber was closed via rolling gates mounted on wheels. A recess in the landward lock wall provided storage for the gates.

A consecutive numbering scheme was used to denote the next four dams that were constructed downstream of Davis Island Dam (Dam 1). Appropriations for these projects were made by various “River and Harbor” acts starting in 1890. Dam 2 was located 9.0 miles downstream of Pittsburgh and was constructed between 1898 and 1906. Construction of Dam 3, located 10.9 miles from Pittsburgh, occurred between 1899 and 1907. Dams 4, 5, and 6 were built between 1892 and 1908 at miles 18.6, 24.1, and 29.3, respectively.

The Board of Engineer officers designated by the River and Harbor Act of 1902 recommended that the navigable depth in the upper Ohio River be increased from six to nine feet. Appropriations for modifications to Dams 2-6 came from the River and Harbor Act of 1905. By

1906, a proposal for a nine foot navigation depth for the entire Ohio River was approved for implementation. The formal authorization for the nine foot depth was provided by the River and Harbor Act of 1910. The original plan called for a total of 54 locks and dams. The projects were divided among four Engineer Districts: Pittsburgh (Dams 1-10), Wheeling (Dams 11-28), Cincinnati (Dams 29-40), and Louisville (Dams 41-54). Of the fifty-four dams originally envisioned, only fifty-one were included in the final plan -- modifying other projects eliminated dams 40, 42, and 54. Each dam had a navigable pass that could be navigated over during high water, and a single 110- by 600-foot lock chamber that could be used the remainder of the time.

Upon completion of a reexamination study of the Ohio River in 1916, it was recommended that fixed dams replace the movable wicket dams. The Emsworth Locks and Dams at mile 6.2 replaced Dams 1 and 2. This was the first time that the concept of movable wicket dams was abandoned in favor of a non-navigable concrete dam. To avoid traffic delays caused by lock closure, two locks were built at the site. The main lock was 110- by 600-feet and the auxiliary lock was 56- by 360-feet. Upon its completion in 1921, the project provided the first non-navigable dam and first twin locks on the Ohio River. In addition, the non-navigable Dashields Locks and Dam was built as a replacement for Dam 3 at mile 13.3. The configuration of Dashields was similar to that of Emsworth. Initial canalization of the Ohio River was finally completed in 1929. Of the fifty lock and dam structures, all but two had a navigable pass.

2.1.4 Intermediate Projects

Following canalization of the Ohio River, several intermediate projects were constructed to enhance navigation conditions. These projects were built prior to the modernization era which began in 1953.

The 56- by 360-foot auxiliary lock chamber at Locks and Dam 41 was completed in 1930. The additional lock substantially increased the capacity of the project. The Emsworth Dams were reconstructed between 1935 and 1938 with gated crests. The upstream pool was raised by seven feet and two lock and dam structures were eliminated.

The storage of water in Tygart Lake, completed in 1938, provided sufficient flows for navigation on the upper Ohio River during dry periods. The project is also part of the comprehensive Ohio River flood control system and provides for water supply and pollution control.

Two new navigation projects were also constructed during this period: Montgomery Locks and Dam in 1936, and Gallipolis Locks and Dam in 1937. Montgomery Locks and Dam, located at mile 31.7, replaced Dams 4, 5, and 6. With a lift of 17.5 feet, it was the first high lift project completed on the Ohio River. The project had two locks measuring 110- by 600-feet and 56- by 360- feet. The Gallipolis Locks and Dam at mile 279.2 replaced three dams on the Ohio River and three on the Kanawha River. It was the most modern lock and dam project of its time. Both locks were 110 feet wide with lock lengths of 600 feet and 360 feet. The original purpose of the Gallipolis project was to improve navigation conditions on the Kanawha River; however, it is operated as part of the Ohio River system. By replacing six existing locks and dams, the Gallipolis Locks and Dam reduced operation and maintenance costs. In addition, the movement of river traffic was expedited as a result of fewer lockages. After completion of the Gallipolis project, there were forty one movable wicket dams and five non-navigable dams on the Ohio River.

2.1.5 Modernization

River traffic on the Ohio River declined during the Great Depression but resumed its climb soon afterward. Traffic increased dramatically, and tow lengths of 1000 feet had come into widespread use. The 600-foot lock chambers became obsolete in the early 1950s and, in some cases, became an impediment to the navigation they were designed to enhance. It became evident that a smaller number of high-lift locks and dams with longer navigation pools would be needed to improve the system. A full-scale modernization program began in 1953. The program provided for the progressive replacement of low lift navigable structures with a smaller number of non-navigable structures with higher lifts. The nine foot navigation channel depth continued as the standard, but lock chamber sizes were increased to accommodate the larger tows. According to river users, a 110- by 1200-foot lock could accommodate the largest tows that could be efficiently operated on the Ohio River. The Corps adopted these dimensions for the main lock chambers at all new projects. In addition, a 110- by 600-foot auxiliary lock chamber was to be provided to improve dependability, flexibility, and capacity.

Construction priority for the new projects was based on the traffic demands of the time. The first modernization project, New Cumberland Locks and Dam, was completed in 1959. Structures at Greenup, Meldahl, and Markland soon followed. By 1979, a total of thirteen new high-lift structures had been built to replace thirty-nine low-lift locks and dams. The new projects had lifts from 16 to 35 feet and pools with an average length of 59 miles. This was a significant improvement over the old structures which had lifts of 5.6 to 11 feet and pool lengths less than 20 miles. All of the new projects had a 110- by 1200-foot main lock chamber and a 110- by 600-foot auxiliary lock chamber. The only exception is Smithland Locks and Dam, which had twin 110- by 1200-foot lock chambers. In addition to the new construction, a 1200-foot lock was built at McAlpine in 1967 to meet the demands of increased traffic. The existing locks at Gallipolis Locks and Dam (renamed R. C. Byrd Locks and Dam) were replaced with a 110- by 1200-foot main lock and a 110- by 600-foot auxiliary lock in 1993. An additional 1200-foot lock chamber is now under construction at McAlpine to replace the inadequate 600-foot auxiliary lock. Only two of the original locks and dams (52 and 53) remain today. They are scheduled to be retired when the last replacement project of the modernization program, Olmsted Locks and Dam, comes on line in 2008. The Olmsted project will have twin 110- by 1200-foot lock chambers. The dam will also incorporate movable steel wickets that will allow free movement of traffic during periods of moderate to high flows.

2.2 EXISTING LOCKS' HYDRAULICS CHARACTERISTICS

Table 2.2-1 was developed to provide basic information about nineteen locks and dams on the Ohio River – eighteen existing structures plus the Olmsted Locks & Dam which is presently under construction to replace Locks 52 and 53.

OHIO RIVER MAINSTEM

TABLE 2.2-1. HYDRAULIC CHARACTERISTICS OF LOCKS

	EMSWORTH	DASHIELDS (Dead Man's Island)	MONTGOMERY	NEW CUMBERLAND	PIKE ISLAND	HANNIBAL	WILLOW ISLAND
GENERAL							
River Mile	6.2	13.3	31.7	54.4	84.2	126.4	161.7
District	Pittsburgh	Pittsburgh	Pittsburgh	Pittsburgh	Pittsburgh	Pittsburgh	Huntington
In-Service Date	1921	1929	1936	1959	1963	1972	1975
Upper Pool Elevation	710	692	682	664.5	644	623	602
Lower Pool Elevation	692	682	664.5	644	623	602	582
Lift (ft)	18	10	17.5	20.5	21	21	20
Top/Lock Elevation	718	704.6	692	674	656	633	616
Lock/Out Elevation	714	701	688	670.1	651.1	629	611
LOCK SIZES							
Main Lock	600' x 110'	600' x 110'	600' x 110'	1200' x 110'	1200' x 110'	1200' x 110'	1200' x 110'
Auxiliary Lock	360' x 56'	360' x 56'	360' x 56'	600' x 110'	600' x 110'	600' x 110'	600' x 110'
FILLING/EMPTYING SYSTEM							
Main Lock Type	Multivalve-Direct	Side Port	Side Port	Side Port	Side Port	Side Port	Side Port
Culvert Size	N/A	11' x 14'-7"	11' x 14'-7"	15'-6" x 15'-6"	15'-6" x 15'-6"	15' x 16'	16' x 18'
Operating Valves	5'4"Butterfly (13)	Butterfly	Butterfly	Reverse Tainter	Reverse Tainter	Reverse Tainter	Reverse Tainter
Discharge Locatn	River - Direct	Lower Approach	Lower Approach	Lower App+River	River - Direct	River - Direct	River - Direct
Depth Over Sill	17.0' U - 12.9'L	13.4'U - 18.5'L	16.0'U - 14.6'L	12.5'U - 14.8'L	17.0'U - 14.8'L	35.8'U - 14.8'L	27.4'U - 15.0'L
Aux Lock Type	Multivalve-Direct	Side Port (R Wall)	Side Port (R Wall)	Bottom Lateral	Bottom Lateral	Bottom Lateral	Bottom Lateral
Culvert Size	N/A	10' x 12'	10' x 12'	15'-6" x 15'-6"	15'-6" x 15'-6"	15' x 16'	16' x 18'
Operating Valves	5'-4" Butterfly (6)	Butterfly	Butterfly	Reverse Tainter	Reverse Tainter	Reverse Tainter	Reverse Tainter
Discharge Locatn	River - Direct	River + Low App	River + Low App	Lower Approach	River - Direct	River - Direct	River - Direct
Depth Over Sill	15.5'U - 12.9'L	13.4'U - 18.5'L	16.0'U - 14.6'L	12.5'U - 14.8'L	17.0'U - 14.8'L	17.0'U - 14.8'L	27.4'U - 15.0'L
APPROACH WALLS							
Main Lock - Upper Wall							
Type	Guide	Guide	Guide	Guard (Ported)	Guard (Ported)	Guard (Ported)	Guard (Ported)
Length (Useable)	525'	490'	489'	1082'	1074'	1200'	1201'
- Lower Wall							
Type	Guard	Guide	Guide	Guard (Solid)	Guard (Solid)	Guard (Solid)	Guard (Solid)
Length (Useable)	577'	491'	490'	1057'	1054'	1440'	1091'
Aux Lock - Upper Wall							
Type	Guard (Ported)	Guard (Ported)	Guard (Ported)	Guide	Guide	Guide	Guide
Length (Useable)	145'	163'	110'	352'	444'	398'	364'
- Lower Wall							
Type	Guard (Solid)	Guard (Ported)	Guard (Solid)	Guard	Guard	Guard	Guard
Length (Useable)	199'	111'	161'	462'	465'	204'	398'
NAVIGABLE WEIRS							
Type	None	None	None	None	None	None	None
Length	N/A	N/A	N/A	N/A	N/A	N/A	N/A
REMARKS							

NOTES: "Useable" Length of approach walls means that length of wall available to an approaching tow for landing.
"Depth over sill" means depth over highest feature in the approach, usually a bulkhead sill

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OHIO RIVER MAINSTEM

TABLE 2.2-1. HYDRAULIC CHARACTERISTICS OF LOCKS (continued)

	BELLEVILLE	RACINE	R C BYRD (Gallipolis)	GREENUP	MELDAHL (New Richmond)	MARKLAND
GENERAL						
River Mile	203.9	237.5	279.2	341	436.2	531.5
District	Huntington	Huntington	Huntington	Huntington	Huntington	Louisville
In-Service Date	1965	1967	1993	1959	1962	1959
Upper Pool Elevation	582	560	538	515	485	455
Lower Pool Elevation	560	538	515	485	455	420
Lift (ft)	22	22	23	30	30	35
Top/Lock Elevation	596	580	560	537	505	466
Lock/Out Elevation	591	575		531	499	463
LOCK SIZES						
Main Lock	1200' x 110'	1200' x 110'	1200' x 110'	1200' x 110'	1200' x 110'	1200' x 110'
Auxiliary Lock	600' x 110'	600' x 110'	600' x 110'	600' x 110'	600' x 110'	600' x 110'
FILLING/EMPTYING SYSTEM						
Main Lock Type	Split Lateral	Side Port	Side Port	Split Lateral	Split Lateral	Split Lateral
Culvert Size	15' x 16'	15'x16'(15'x18'@Ports)	16' x 18'	16' x 18'	16' x 18'	16' x 18'
Operating Valves	Reverse Tainter	Reverse Tainter	Reverse Tainter	Reverse Tainter	Reverse Tainter	Reverse Tainter
Discharge Location	River - Direct	River - Direct	River - Direct	River - Direct	River - Direct	River - Direct
Depth Over Sill	20.0'U - 15.0'L	18.0'U - 15.0'L	18.0'U - 18.0'L	18.0'U - 15.0'L	18.0'U - 15.0'L	25.0'U - 15.0'L
Aux Lock Type	Bottom Lateral	Bottom Lateral	Bottom Lateral	Bottom Lateral	Bottom Lateral	Bottom Lateral
Culvert Size	15' x 16'	15' x 16'	16' x 18'	16' x 18'	16' x 18'	16' x 18'
Operating Valves	Reverse Tainter	Reverse Tainter	Reverse Tainter	Reverse Tainter	Reverse Tainter	Reverse Tainter
Discharge Location	River - Direct	River - Direct	River - Direct	River - Direct	River - Direct	River - Direct
Depth Over Sill	20.0'U - 15.0'L	18.0'U - 15.0'L	28.0'U - 18.0'L	18.0'U - 15.0'L	18.0'U - 15.0'L	25.0'U - 15.0'L
APPROACH WALLS			(Upper Approach in Canal)			
Main Lock - Upper Wall						
Type	Guard (Ported)	Guard (Ported)	Guard	Guard (Ported)	Guard (Ported)	Guard (Ported)
Length (Useable)	1168'	1200'	1200'	1200'	1200'	1197'
- Lower Wall						
Type	Guard (Solid)	Guard (Solid)	Guard	Guard (Solid)	Guard (Solid)	Guard (Solid)
Length (Useable)	1091'	1090'	1000'	1050'	1090'	1050'
Aux Lock - Upper Wall						
Type	Guide	Guide	Guard	Guide	Guide	Guide
Length (Useable)	316'	370'	262'	382'	382'	379'
- Lower Wall						
Type	Guard	Guard	Guard	Guard	Guard	Guard
Length (Useable)	440'	371'	490'	380'	340'	380'
NAVIGABLE WEIRS						
Type	None	None	None	None	None	None
Length	N/A	N/A	N/A	N/A	N/A	N/A
REMARKS						

NOTES: "Useable" Length of approach walls means that length of wall available to an approaching tow for landing.
"Depth over sill" means depth over highest feature in the approach, usually a bulkhead sill

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OHIO RIVER MAINSTEM

TABLE 2.2-1. HYDRAULIC CHARACTERISTICS OF LOCKS (continued)

	McALPINE	CANNELTON	NEWBURGH	J T MYERS	SMITHLAND	OLMSTED
GENERAL	(L/D 41)			(Uniontown)	(Dog Island)	(Under Construction)
River Mile	606.8	720.7	776.1	846	918.5	964.4
District	Louisville	Louisville	Louisville	Louisville	Louisville	Louisville
In-Service Date	1961-2003	1971	1975	1975	1979	2008 (Scheduled)
Upper Pool Elevation	420	383	358	342	324	295-301
Lower Pool Elevation	383	358	342	324	302	Uncontrolled
Lift (ft)	37	25	16	18	22	21 (Nominal)
Top/Lock Elevation	443	402	380	362	344	310
Lock/Out Elevation	440	399	377	359	341	295-301
LOCK SIZES						
Main Lock	1200' x 110'	1200' x 110'	1200' x 110'	1200' x 110'	1200' x 110'	1200' x 110'
Auxiliary Lock	1200' x110' (2003)	600' x 110'	600' x 110'	600' x 110'	1200' x 110'	1200' x 110'
FILLING/EMPTYING SYSTEM						
Main Lock Type	Split Lateral (Existing)	Side Port	Side Port	Side Port	Side Port	Side Port
Culvert Size	16' x 18'	16' x 18'	14' x 16'	14' x 16'	14' x 18'	14' x 18'
Operating Valves	Reverse Tainter	Reverse Tainter	Reverse Tainter	Reverse Tainter	Reverse Tainter	Reverse Tainter
Discharge Location	River - Direct	River - Direct	River - Direct	River - Direct	River - Direct	River - Direct
Depth Over Sill	18.0'U - 12.0'L	15.0'U - 15.0'L	18.0'U - 16.0'L	20.0'U - 16.0'L	34.0'U - 15.0'L	34' to 40'U - 18'L
Aux Lock Type	Central Culverts (UC)	Bottom Lateral	Bottom Lateral	Bottom Lateral	Side Port	Side Port
Culvert Size	16' x 18'	16' x 18'	14' x 16'	14' x 16'	14' x 18'	14' x 18'
Operating Valves	Reverse Tainter	Reverse Tainter	Reverse Tainter	Reverse Tainter	Reverse Tainter	Reverse Tainter
Discharge Location	Lower Approach	River - Direct	River - Direct	River - Direct	River - Direct	River - Direct
Depth Over Sill	18.0'U - 16.0'L	15.0'U - 15.0'L	18.0'U - 16.0'L	20.0'U - 16.0'L	34.0'U - 15.0'L	34' to 40'U - 18'L
APPROACH WALLS	(Upper Approach in Canal)					
Main Lock - Upper Wall						
Type	Guard (Ported)	Guard (Ported)	Guard (Ported)	Guard (Ported)	Guard (Ported)	Guard (Floating)
Length (Useable)	1010'	1188'	1190'	1198'	900'	900'
- Lower Wall						
Type	Guard (Ported)	Guard (Solid)	Guard (Solid)	Guard (Solid)	Guard (Solid)	Guard (Floating w/ Curtains)
Length (Useable)	1094'	1002'	1009'	998'	1050'	852'
Aux Lock - Upper Wall						
Type	Guide	Guide	Guide	Guide	Guard (Ported)	Guard (Floating)
Length (Useable)	390'	430'	310'	310'	600'	767'
- Lower Wall						
Type	Guide	Guide	Guard	Guard	Guide	Guide (Fixed)
Length (Useable)	600'	439'	426'	448'	450'	359'
NAVIGABLE WEIRS						
Type	None	None	1300'	2100'	1572'	1400'
Length	N/A	N/A	Fixed	Fixed	Fixed	Boat Operated Wickets
REMARKS						

NOTES: "Useable" Length of approach walls means that length of wall available to an approaching tow for landing.
"Depth over sill" means depth over highest feature in the approach, usually a bulkhead sill
"Aux Lock" refers to the landward 1200' lock at the McAlpine, Smithland and Olmsted projects.

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SECTION 3

OHIO RIVER HYDROLOGY AND HYDRAULICS

The Ohio River flows through three districts (Pittsburgh, Huntington and Louisville) of the Great Lakes and Ohio River Division. There exists in the three district offices much hydrology information that is useful to the Ohio River Mainstem Systems Study (ORMSS). The data are collected and retained in different formats depending on the capabilities of the satellite, number of DCP's, computer systems, etc. Also the length of record, time intervals of the data, and presentation will vary from district to district. New technology, such as the Internet, world wide web and home pages have made hydrology information readily available to other Corps of Engineers districts, federal and state agencies, architect-engineers, and the general public. The information, tables and plates presented in the following paragraphs highlight types of available data. Except for a table of the lake projects in the Ohio River Basin, only samples of available data will be presented in this part of the ORMSS report. The lakes in each district will show only the drainage area and the year its operation began because they are two of the main pieces of information needed to evaluate how a historical flood profile would be affected by existing conditions. If a full period of record data is required for a project, it will be in the volume titled, "(Study Project) Lock & Dam Site Engineering Appendix.

3.1 BASIN CHARACTERISTICS

The Ohio River is unique in that the stream mileage is measured from its headwater location in Pittsburgh, where the Allegheny and the Monongahela Rivers meet to form the Ohio River downstream approximately 981 miles until it empties into the Mississippi River near Cairo, IL. The total drainage area of the Ohio River Basin is 203,943 square miles.

The Pittsburgh District, known as the Headwaters District is comprised of the Ohio River drainage basin above New Martinsville, WV. The downstream limit of the Pittsburgh District is at river mile 127.2. The District covers an area of approximately 67,000 square kilometers (26,000 square miles), including portions of Pennsylvania, West Virginia, Ohio, New York and Maryland. Major river systems within the District include the upper Ohio, the Allegheny, the Monongahela and the Beaver Rivers. The District manages 16 flood control and multipurpose reservoirs with a combined capacity of over 3.8 billion cubic meters (3 million acre-feet) and 23 navigation locks and dams on 530 kilometers (330 miles) of navigable waterways. Six of the locks and dams are on the Ohio River.

The Huntington District lies downstream on the Ohio River from the Pittsburgh District and the reach stretches from stream mile 127.2 to 438.0. The Louisville District has the longest reach of the Ohio River from mile 438.0 at the Huntington District line to its mouth (mile 981.0) at the Mississippi River.

3.1.1 General Topography

The topography of the Ohio River Valley varies greatly from its origin in Pittsburgh, PA where the Allegheny and Monongahela Rivers meet to form the headwaters of the Ohio River to its mouth at the Mississippi River. The main stem of the Ohio River flows in a general southwesterly direction, falling 429 feet in its 981-mile course from Pittsburgh to Cairo. The flood plain is rather narrow, owing largely to the river's creation at the southern edge of Ice Age glacial action.

In the Pittsburgh District, the valley floor averages about 0.8 miles in width and the natural gradient of the streambed is about 1.0 feet per mile. Present stream banks generally average 20-25 feet in height except in the Emsworth pool where they average 10-15 feet high. Several islands are found in the Ohio River and the highly industrialized Neville Island is located in the Emsworth and Dashields pools.

The flood plain width averages more than a mile between Cincinnati and Louisville. At Louisville, the Ohio River floodplain widens to approximately four miles and then contracts to a mile below the Salt River. However, a floodwall around Jefferson County and the city of Louisville in Kentucky along with New Albany and Jeffersonville, Indiana floodwalls, limits the width to about a mile. Near the mouth, the Ohio River floodplain again widens to about six to eight miles. Elevations vary from 100 to 600 feet below the plateaus surrounding the valley. The only falls are at Louisville, where a 26-feet difference in water surface between the upper and lower pools existed prior to canalization. Numerous islands have been formed in the river over the centuries. Large bends or oxbows in the river give the stream a picturesque look. However in some areas like the Kentucky Peninsula across the stream from Evansville, Indiana, floodwaters have caused erosion problems and threaten to cut through the oxbow from the continuous flooding of the land.

3.1.2 Major Tributaries

Tributaries in the Ohio River Basin vary from very steep mountain streams with cascades and rapids to sluggish, meandering, marsh-like areas. Slopes of major tributaries vary from more than 100 feet per mile in the headwaters to less than two-tenths of a foot per mile in the flat areas near the main stem. In general, the streams are considerably steeper in the headwaters, becoming relatively flat near the mouth. Post-glacial changes in stream patterns, local layers of hard rock and distribution of tributaries may cause local modifications in profiles.

Table 3.1.2-1, titled "Ohio River & Tributaries Drainage Areas", has been developed which shows the river mile and total drainage area at major communities, former dam locations, and at the present locks and dams. Also provided are the river miles of major tributaries, which shows the contributing drainage area to the Ohio River at that point. As shown in Table 3.1.2-1, the Pittsburgh District has information on the lengths and average slopes of the main tributaries.

Table 3.1.2-1 Ohio River & Tributaries Drainage Areas

RIVER MILE	SITE	BANK	DRAINAGE AREA (SQ. MI.)	LENGTH (MILES)	AVERAGE SLOPE (FEET/MILE)	OHIO RIVER DRAINAGE AREA (SQ. MI.)
	Allegheny River					**11,748**
	Monongahela River					**7,384**
	Head of the Ohio River					**19,132**
0.7	Saw Mill Run	Left	19.4	9.6	47.0	
2.6	Chartiers Creek	Left	277.0	52.0	11.0	
6.2	**Emsworth Locks & Dam**					**19,428**
6.2	Lowries Run	Right	17.0	8.3	55.0	
9.4	Montour Run	Left	36.6	11.5	43.0	
11.8	**Sewickley, PA**					**19,500**
13.3	**Dashields Locks & Dam**					**19,522**
15.4	Big Sewickley Creek	Right	30.2	10.5	40.0	
22.2	Crows Run	Right	13.8	7.4	55.0	
25.4	Beaver River	Right	3153.0	87.5	3.4	
29.6	Raccoon Creek	Left	184.0	45.0	12.0	
31.7	**Montgomery Locks & Dam**					**22,969**
39.5	Little Beaver Creek	Right	503.0	15.9	12.1	
40.1	Mill Creek	Left	15.5	6.3	73.0	
47.1	Little Yellow Creek	Right	22.7	10.4	43.6	
50.4	Yellow Creek	Right	239.0	32.1	10.1	
54.4	**New Cumberland Locks & Dam**					**23,870**
60.1	Kings Creek	Left	49.6	14.2	36.3	
61.7	Island Creek	Right	26.4	9.3	57.3	
66.7	Harmon Creek	Left	39.0	16.3	37.3	
71.6	Indian Cross Creek	Right	128.0	30.5	19.8	
71.6	Virginia Cross Creek	Left	79.9	23.2	26.0	
74.7	Buffalo Creek	Left	163.0	39.8	13.5	
81.4	Indian Short Creek	Right	148.0	24.4	23.4	
81.5	Virginia Short Creek	Left	24.4	10.1	56.4	
84.2	**Pike Island Locks & Dam**					**24,639**
90.2	Wheeling Creek, OH	Right	108.0	31.0	18.0	
85-93	**Wheeling, WV**					**24,800**
90.7	Wheeling Creek, WV	Right	298.0	29.35	7.9	
94.7	McMahon Creek	Right	91.0	27.9	20.4	
102.4	Grave Creek	Left	74.8	22.2	29.1	
109.6	Captina Creek	Right	180.0	25.9	10.2	
113.8	Fish Creek	Left	229.0	26.85	7.1	
118.0	Sunfish Creek	Right	114.0	31.4	16.3	
119.8	Opossum Creek	Right	25.4	13.0	47.3	
122.3	Proctor Creek	Left	22.0	8.9	53.7	
126.4	**Hannibal Pool Locks & Dam**					**25,960**

TABLE 3.1.2-1 Ohio River & Tributaries (continued)
Drainage Areas

RIVER MILE	SITE	BANK	DRAINAGE AREA (SQ. MI.)	LENGTH (MILES)	AVERAGE SLOPE (FEET/MILE)	OHIO RIVER DRAINAGE AREA (SQ. MI.)
127.2	**Pittsburgh-Huntington District Line**					**25,966**
155.0	**St. Marys, WV**					**26,850**
161.7	**Willow Island Locks and Dam**					**26,900**
172.2	Muskingum River	Right	8040			
184.4	**Parkersburg, WV**					**35.600**
184.6	Little Kanawha River	Left	2320			
199.3	Hocking River	Right	1190			
203.9	**Belleville Locks and Dam**					**39,302**
237.5	**Racine Locks and Dam**					**40,130**
265.3	**Pomeroy, OH**					**40,500**
265.7	Kanawha River	Left	12,200			
265.8	**Point Pleasant**					**52,760**
279.2	**R.C. Byrd (Gallipolis) Locks and Dam**					**53,300**
305.2	Guyandotte River	Left	1670			
311.6	**Huntington, WV**					**55,900**
317.1	Big Sandy River	Left	4294			
322.5	**Ashland, KY**					**60,750**
341.0	**Greenup Locks and Dam**					**62,000**
356.5	Scioto River	Right	6510			
408.6	**Maysville, KY**					**70,130**
436.2	**Meldahl Locks and Dam**					**70,808**
438.0	**Huntington-Louisville District Line**					**70,820**
464.1	Little Miami River	Right	1760			
470.2	Licking River	Left	3707			
470.5	**Cincinnati, OH**					**76,580**
491.1	Great Miami River	Right	5400			
531.5	**Markland Locks and Dam**					**83,170**
545.7	**above Kentucky River**					**83,320**
545.8	Kentucky River	Left	6966			
557.7						**90,580**
607.3	**McAlpine Locks and Dam**					**91,170**
627.1	**Kosmosdale**					**91,440**
629.9	Salt River	Left	2920			
633.2	**Dam 43**					**94,440**
663.2	**Dam 44**					**95,685**
703.0	**Dam 45**					**96,260**

TABLE 3.1.2-1 Ohio River & Tributaries (continued)
Drainage Areas

RIVER MILE	SITE	BANK	DRAINAGE AREA (SQ. MI.)	LENGTH (MILES)	AVERAGE SLOPE (FEET/MILE)	OHIO RIVER DRAINAGE AREA (SQ. MI.)
720.7	**Cannelton Locks and Dam**					**97,000**
727.8	**Tell City**					**96,750**
757.3	**Dam 46**					**97,180**
755-757	**Owensboro, KY**					**97,200**
776.1	**Newburgh Locks and Dam**					**97,690**
777.7	**Dam 47**					**97,690**
784.2	Green River	Left	9230			
792.4	**Evansville**					**107,000**
803.9	**Henderson, KY**					**107,600**
809.6	**Dam 48**					**107,600**
829.2	**Mt. Vernon, IN**					**107,700**
845.0	**Dam 49**					**107,965**
846.0	**J.T. Myers Locks and Dam** **(Uniontown)**					**108,000**
848.0	Wabash River	Right	33,100			
867.3	Saline River	Right	1170			
873.4	Tradewater River	Left	1000			
876.8	**Dam 50**					**143,400**
903.1	**Dam 51 (Golconda, IL)**					**143,900**
918.5	**Smithland Locks and Dam**					**144,000**
920.4	Cumberland River	Left	17,920			
934.5	Tennessee River	Left	40,910			
934.8	**Paducah**					**202,800**
938.9	**Dam 52**					**202,830**
943.6	**Metropolis, IL**					**203,000**
962.6	**Dam 53 (near Grand Chain, IL)**					**203,100**
964.4	**Olmsted Locks and Dam (Under Const.)**					**203,100**
974.2	**Mound City, IL**					
981.0	**Mouth of the Ohio River**					**203,943**

3.2 HYDROLOGY

3.2.1 Upstream Reservoir And Flood Protection Projects

The January 1937 basin-wide flood and the increase in industry tow traffic made a major impact on the water facilities in the three districts. Although a few flood control and multipurpose lakes were completed or were under construction in 1937, many more dams and lakes were built after this flood so that at present there are 72 lake projects. This does not include projects in the Nashville District, which affect the Ohio River below the Cumberland and Tennessee Rivers. These rivers enter in the lower reach of the Ohio River where two 1200' locks already exist at Smithland Locks & Dam and where construction is underway on two 1200' locks at Olmsted Lock & Dam (total project completion date is 2008). A list of reservoirs with their drainage areas and approximate date of completion are shown on Table 3.2.1-1.

There are no Corps of Engineers local flood protection projects consisting of floodwalls, levees or dikes along the main stem Ohio River in the Pittsburgh District. However, there are numerous local protection projects in the Huntington and Louisville Districts. These local protection projects will not be affected by expanded and added lock projects since pool levels would not be changed.

TABLE 3.2.1-1 LAKE PROJECTS IN THE OHIO RIVER BASIN

RIVER BASIN	LAKE PROJECT	DRAINAGE AREA	IN OPERATION DATE PLACED
	PITTSBURGH DISTRICT		
Allegheny River, Pennsylvania	Kinzua Dam and Allegheny Reservoir	2,180 sq. mi.	1967
	Tionesta Lake	478 sq. mi.	1940
	Union City Dam	222 sq. mi.	1971
	Woodcock Creek Lake	45.7 sq. mi.	1974
	East Branch Clarion River Lake	72.4 sq. mi.	1952
	Mahoning Creek Lake	340 sq. mi.	1941
	Crooked Creek Lake	277 sq. mi.	1940
	Conemaugh River Lake	1,351 sq. mi.	1952
	Loyalhanna Lake	290 sq. mi.	1942
Monongahela River, West Virginia	Stonewall Jackson Lake	102 sq. mi.	
	Tygart Lake	1,184 sq. mi.	1938
Monongahela River, Maryland	Youghiogheny River	434 sq. mi.	1948
Beaver River, Ohio	M. J. Kirwan Dam and Reservoir	80.5 sq. mi.	1967
	Berlin Lake	249 sq. mi.	1943
	Mosquito Creek Lake	97.4 sq. mi.	1944
Beaver River, Pennsylvania	Shenanro River Lake	589 sq. mi.	1967
	HUNTINGTON DISTRICT		
Muskingum River, Ohio	Atwood Lake	70 sq. mi.	1937
	Beach City Lake	300 sq. mi.	1937
	Bolivar Lake	502 sq. mi.	1938
	Charles Mill Lake	215 sq. mi.	1936
	Clendening Lake	69 sq. mi.	1937
	Dillon Lake	742 sq. mi.	1961
	Dover	1,397 sq. mi.	1938
	Leesville Lake	48 sq. mi.	1937
	Mohawk Lake	1,504 sq. mi.	1937
	Mohicanville Lake	271 sq. mi.	1937
	North Branch of Kokosing Lake	44.5 sq. mi.	1971

TABLE 3.2.1-1 LAKE PROJECTS IN THE OHIO RIVER BASIN (continued)

RIVER BASIN	LAKE PROJECT	DRAINAGE AREA	IN OPERATION DATE PLACED
	Piedmont Lake	86 sq. mi.	1937
	Pleasant Hill Lake	197 sq. mi.	1938
	Senecaville Lake	118 sq. mi.	1937
	Tappan Lake	71 sq. mi.	1936
	Wills Creek Lake	842 sq. mi.	1937
	Salt Fork Lake		
Little Kanawha River, West Virginia	Burnsville Lake	165 sq. mi.	1978
Hocking River, Ohio	Tom Jenkins Dam	32.8 sq. mi.	1952
Kanawha River, West Virginia	Bluestone Lake	4,565 sq. mi.	1949
	Summersville Lake	803 sq. mi.	1964
	Sutton Lake	537 sq. mi.	1960
Guyandotte River, West Virginia	R. D. Bailey Lake	540 sq. mi.	1980
Twelvepole River, West Virginia	East Lynn Lake	133 sq. mi.	1972
	Beech Fork Lake	78 sq. mi.	1978
Big Sandy River, Kentucky	J. W. Flannagan Lake	221 sq. mi.	1963
	North Fork of Pound Lake	17.2 sq. mi.	1964
	Fishtrap Lake	395 sq. mi.	1969
	Dewey Lake	207 sq. mi.	1950
	Paintsville Lake	92.5 sq. mi.	1983
	Yatesville Lake	208 sq. mi.	
Little Sandy River, Kentucky	Grayson Lake	196 sq. mi.	1969
Scioto River, Ohio	Delaware Lake	381 sq. mi.	1948
	Alum Creek Lake	123 sq. mi.	1974
	Deer Creek Lake	277 sq. mi.	1968
	Paint Creek Lake	573 sq. mi.	1974
	LOUISVILLE DISTRICT		
Little Miami River, Ohio	Caesar Creek Lake	237 sq. mi.	January 1978
	William H. Harsha Lake	342 sq. mi.	February 1979
Licking River, Kentucky	Cave Run Lake	826 sq. mi.	February 1974
Mill Creek, Ohio	West Fork of Mill Creek Lake	29.5 sq. mi.	December 1952

TABLE 3.2.1-1 LAKE PROJECTS IN THE OHIO RIVER BASIN (continued)

RIVER BASIN	LAKE PROJECT	DRAINAGE AREA	IN OPERATION DATE PLACED
Miami River, Ohio	Clarence J. Brown Dam and Reservoir	82 sq. mi.	January 1974
Whitewater River, Indiana	Brookville Lake	379 sq. mi.	January 1974
Kentucky River, Kentucky	Carr Creek Lake	58 sq. mi.	January 1976
	Buckhorn Lake	408 sq. mi.	December1961
Salt River, Kentucky	Taylorsville Lake	353 sq. mi.	January 1983
Green River, Kentucky	Green River Lake	682 sq. mi.	June 1969
	Nolin River Lake	703 sq. mi.	March 1963
	Barren River Lake	940 sq. mi.	October 1964
	Rough River Lake	454 sq. mi.	September 1959
Wabash River, Indiana	J. Edward Roush Lake	707 sq. mi.	October 1968
	Salamonie Lake	553 sq. mi.	September 1966
	Mississinewa Lake	809 sq. mi.	October 1967
	Cecil M. Harden Lake	216 sq. mi.	July 1960
	Cagles Mill Lake	295 sq. mi.	June 19553
	Monroe Lake	441 sq. mi.	February 1965
	Patoka Lake	168 sq. mi.	August 1980
	NASHVILLE DISTRICT		
Cumberland River, Kentucky	Martin's Fork Lake	55.7 sq. mi.	1978
	Laurel River Lake	282 sq. mi.	1977
	Lake Cumberland	5,789 sq. mi.	1950
Cumberland River, Tennessee	Dale Hollow Lake	935 sq. mi.	1943
	Cordell Hull Lake	8,096 sq. mi.	1973
	Center Hill Lake	2,174 sq. mi.	1948
	Old Hickory Lake	11,674 sq. mi.	1957
	J.Percy Priest Lake	892 sq. mi.	1967
	Cheatham Lake	14,160 sq. mi.	1959
Cumberland River, Kentucky	Lake Barkley	17,598 sq. mi.	1966

3.2.2 Stream Gaging Stations and Records

The records of flooding in the Pittsburgh area were obtained at Fort Duquesne at the junction of the Allegheny and Monongahela Rivers as early as 1765. Later, when navigation became a more dominant factor in colonial activity, gages were established on the Monongahela River wharf and records are found from this source.

The collection of systematic hydrologic records on the Ohio River dates back to the flood heights recorded at Pittsburgh in 1806. At first, only significant hydrologic events were recorded. These events usually consisted of floods of unusual magnitude, extent or duration. It was not until 1855, when the U.S. Army Signal Corps made regular daily observations, later replaced by the U.S. Weather Bureau in 1878, that continuous records became available. However, continuous record collection on the Ohio River began at Pittsburgh in 1847, Cincinnati in 1858, and Louisville in 1866. Each district maintains a database of hydrologic information for their respected reach. Continuous hydrologic records are kept at locks and dams on the Ohio River. In addition, many communities and flood control projects have gages that provide a continuous record. Records of stage are most readily available with stream flow records being less common.

Corps of Engineers (COE) Pittsburgh District staff gages are located on the upper and lower lock walls at Emsworth, Dashields, Montgomery, New Cumberland, Pike Island and Hannibal Locks and Dams. Auxiliary staff gages are installed above the lock walls to measure high water events. Staff gage measurements are taken by lock personnel and have been recorded since the time of construction in three-hour increments and hourly during high water events. Each dam has a critical river height at which these hourly readings are recorded and this procedure continues until the river recedes below this stage.

Digital automatic stage records are available for the Ohio River at Pittsburgh's "Point" gage, the upper and lower pools at Emsworth Locks and Dam, New Cumberland Locks and Dam, Pike Island Locks and Dam and Hannibal Locks and Dam. The measurement equipment includes chart recorders and remote transmitters. The digital readouts are located within the projects for the purpose of continuous monitoring.

Data Collection Platform (DCP) gages are located on the Ohio River at Emsworth Locks and Dam, East Liverpool, New Cumberland Locks and Dam, Pike Island Locks and Dam, Wheeling, Dilles Bottom, and Hannibal Locks and Dam. The stage readings are automatically recorded and transmitted to the Pittsburgh District's data storage system using satellite telemetry. They have been in operation since the early 1980's.

River stage readings have been recorded at the USGS gaging station, Ohio River at Sewickley, Pennsylvania since October 1933. Currently, an automatic continuous recording DCP gage with satellite telemetry is located on the upstream side of Dashields Locks and Dam. This station has a fixed-crest dam control, which merits it with a good stage-discharge relationship.

Table 3.2.2-1
Pittsburgh District
Historical Minimum and Maximum Flow Rates
at Various Gaging Stations (Flow in cfs)

Station	Drainage Area	Period of Record	Minimum Flow	Date	Maximum Flow	Date
Ohio River						
Sewickley, PA	19,522	1933-date	1800	9/57	574,000	3/36
New Cumberland L/D	23,873	1959-date	----	----	386,000	6/72
Wheeling, WV	24,666	1838-date	----	----	373,000	6/72

Over the years flow measurements have been made to develop rating curves at gage locations to show the relationship between stage and flow. The stage data that is obtained provides instantaneous information and together with highwater marks form the basis of the historical flood profiles.

The locations of various stream flow gages in the Huntington and Louisville Districts, together with other pertinent data, are contained in Table 3.2.2-2 and 3.2.2-3. Although not discussed in detail as for the Pittsburgh District above, the Huntington and Louisville Districts have staff gages, digital automatic stage recorders, DCP gages with satellite telemetry to provide instantaneous and continuous recording of data.

Data is available from the files of Table 3.2.2-3 in the Louisville District so that annual peaks and all peaks above a specified elevation can be provided both chronologically and in order of magnitude for the period of record. An example for the J. T. Myers upper gage is provided in Table 3.2.2-4.

Table 3.2.2-2 Huntington District
Ohio River Stream Flow Gaging Stations

Station Locations	River Mile	Drainage Area (square miles)	Period of Record	Maximum Stage (ft)	Gage Datum (ft)
Saint Marys, WV	155.0	26,850	1913-1972	54.20	577.30 (1)
Marietta, OH	174.3	35,600	1968-Present	38.52	567.12 (1)
Pomeroy, OH	251.3	40,520	1913-1968	55.00	514.10 (1)
Point Pleasant, WV	265.2	52,760	1940-Present	55.00	514.00 (1)
Huntington, WV	308.3	55,900	1935-Present	61.60	490.26 (1)
Ashland, KY	322.5	60,750	1884-Present	73.60	483.10 (1)
Greenup L&D	341.0	62,000	1968-Present	50.96	472.97 (2)
Maysville, KY	408.6	70,130	1937-Present	75.30	451.50 (1)

(1.) Denotes Sandy Hook Datum.
(2.)Denotes 1929 Datum.

Table 3.2.2-3
Louisville District   Ohio River Stations

			ORD DATUM	
001	EVANSVILLE	792.3	329.2	1930-1999
100	MT VERNON	829.2	318.9	1930-1991
300	TELL CITY (COMPOSITE)	727.7	347.6	1930-1991
390	MARKLAND (CLG)	531.9	408.0	1930-1999
391	MARKLAND (UPR)	531.2	443.0	1963-1999
392	MARKLAND (LWR)	531.9	408.0	1963-1999
393	LOCK 39 (LWG)	531.7	411.0	1930-1936
401	J.T.MYERS (UPR)	845.8	330.0	1970-1999
402	J.T.MYERS (LWR)	846.2	312.0	1970-1999
410	MCALPINE (CLG)	606.8	374.0	1976-1982
411	MCALPINE (UPR)	607.3	408.0**	1875-1999
412	MCALPINE (LWR)	606.8	374.0	1875-1999
415	MCALPINE (WWG)	606.8		1961-1970
420	KOSMOSDALE	627.1	374.0	1972-1999
510	GOLCONDA + LD51 (CLG)	903.2	293.0	1930-1980
511	GOLCONDA + LD51 (UPR)	902.9	294.6	1930-1989
515	PADUCAH	934.6	286.3	1965-1999
520	BROOKPORT LK52 (CLG)	938.7	281.0	1930-1995
521	BROOKPORT LK52 (UPR)	939.1	283.3	1930-1999
522	BROOKPORT LK52 (LWR)	938.7	281.0	1930-1999
530	LOCK 53 (CLG)	962.4	273.1	1930-1995
531	LOCK 53 (UPR)	962.8	273.1	1930-1999
532	LOCK 53 (LWR)	962.4	273.1	1930-1999
534	GRAND CHAIN RECORDING	962.1	276.6	1930-1969
555	SMITHLAND(UPR)	918.8	312.0	1981-1999
556	SMITHLAND(LWR)	918.3	290.0	1981-1999
601	CANNELTON(UPR)	720.5	374.0	1971-1999
602	CANNELTON(LWR)	720.9	348.0	1968-1999
701	NEWBURGH(UPR)	775.9	348.0	1971-1999
702	NEWBURGH(LWR)	776.3	330.0	1971-1999
800	CAIRO	979.5	270.9	1930-1999
802	MELDAHL(LWR)	436.7	443.0	1965-1999
900	CINCINNATI	470.5	429.6	1930-1999
901	CINCINNATI(ADJ)	470.5	429.6	1950-1990

*   RIVER MILEAGE ADJUSTED FROM HIGHWATER PROFILES
** STAGE VALUES BEFORE JAN 1965 HAVE BEEN ADJUSTED FOR NEW DATUM

Table 3.2.2-4

OHIO RIVER AT J.T.MYERS(UPR)
RIVER ELEVATION FREQUENCY TABLE
(FOR PERIOD SEP 1975 - OCT 1998)

ANNUAL PEAKS (BY WATER YEAR)

YEAR	PEAK	DATE
1976	355.30	27 FEB 1976
1977	351.60	13 APR 1977
1978	358.70	23 MAR 1978
1979	362.50	08 MAR 1979
1980	352.50	29 MAR 1980
1981	350.80	14 JUN 1981
1982	355.40	26 MAR 1982
1983	360.90	10 MAY 1983
1984	354.20	15 MAY 1984
1985	354.70	05 MAR 1985
1986	356.00	07 DEC 1985
1987	349.70	18 APR 1987
1988	350.90	10 FEB 1988
1989	357.40	24 FEB 1989
1990	356.90	20 FEB 1990
1991	364.00	09 JAN 1991
1992	346.80	09 DEC 1991
1993	353.60	13 MAR 1993
1994	357.20	23 APR 1994
1995	358.80	26 MAY 1995
1996	360.00	15 MAY 1996
1997	366.00	11 MAR 1997
1998	353.90	27 APR 1998

PEAKS IN PERIOD (BY ORDER OF OCCURANCE)

PEAK	DATE
351.10	9 JAN 1976
355.30	27 FEB 1976
351.60	13 APR 1977
351.00	3 FEB 1978
358.70	23 MAR 1978
359.00	18 DEC 1978
352.40	9 JAN 1979
352.50	29 JAN 1979
362.50	8 MAR 1979
354.20	18 APR 1979
352.50	29 MAR 1980
350.80	14 JUN 1981
351.20	29 JAN 1982
351.00	9 FEB 1982
355.40	26 MAR 1982
360.90	11 MAY 1983
353.40	23 MAY 1983
353.50	5 APR 1984
354.10	30 APR 1984
354.20	15 MAY 1984
354.70	5 MAR 1985
351.90	7 APR 1985
356.00	7 DEC 1985
353.00	14 FEB 1986
350.90	10 FEB 1988
357.40	24 FEB 1989
352.20	14 MAR 1989
355.50	9 APR 1989
356.90	21 FEB 1990
351.90	23 MAY 1990
351.00	3 JUN 1990
364.00	9 JAN 1991
354.30	31 MAR 1991
353.60	13 MAR 1993
352.40	4 APR 1993
356.70	6 FEB 1994
352.20	3 MAR 1994
354.10	18 MAR 1994
357.20	23 APR 1994
358.80	26 MAY 1995
357.20	31 JAN 1996
360.00	16 MAY 1996
366.00	13 MAR 1997
353.90	27 APR 1998
352.10	12 MAY 1998

PEAKS IN PERIOD (BY ORDER OF MAGNITUDE)

PEAK	DATE
366.00	13 MAR 1997
364.00	09 JAN 1991
362.50	08 MAR 1979
360.90	11 MAY 1983
360.00	16 MAY 1996
359.00	18 DEC 1978
358.80	26 MAY 1995
358.70	23 MAR 1978
357.40	24 FEB 1989
357.20	23 APR 1994
357.20	31 JAN 1996
356.90	21 FEB 1990
356.70	06 FEB 1994
356.00	07 DEC 1985
355.50	09 APR 1989
355.40	26 MAR 1982
355.30	27 FEB 1976
354.70	05 MAR 1985
354.30	31 MAR 1991
354.20	18 APR 1979
354.20	15 MAY 1984
354.10	30 APR 1984
354.10	18 MAR 1994
353.90	27 APR 1998
353.60	13 MAR 1993
353.50	05 APR 1984
353.40	23 MAY 1983
353.00	14 FEB 1986
352.50	29 JAN 1979
352.50	29 MAR 1980
352.40	09 JAN 1979
352.40	04 APR 1993
352.20	14 MAR 1989
352.20	03 MAR 1994
352.10	12 MAY 1998
351.90	07 APR 1985
351.90	23 MAY 1990
351.60	13 APR 1977
351.20	29 JAN 1982
351.10	09 JAN 1976
351.00	03 FEB 1978
351.00	09 FEB 1982
351.00	03 JUN 1990
350.90	10 FEB 1988
350.80	14 JUN 1981

3.2.3 Historical and Recorded Floods

Storm patterns and the length of the Ohio River can produce record floods occurring in one district with little or no flooding in the other districts. The exception is the January 1937 flood, which was the modern day major flood in the basin.

In the Pittsburgh District, the highest known floods prior to the construction of flood control projects occurred March 15, 1907 with a peak of 732.7 feet above National Geodetic Vertical Datum (NGVD), January 9, 1763 with a peak of 735.1 (NGVD) and March 18, 1936 with a peak of 740.2 feet above NGVD at the Pittsburgh “Point”. Since the 1936 flood, twelve flood control reservoirs have been built in the Allegheny and Monongahela River basins which provide flood protection on the Ohio River from Pittsburgh on downstream. In addition, four reservoirs in the Beaver River basin (built 1943-1967) effect reductions in flood stages in the Montgomery pool and downstream.

The March 1936 (St. Patrick’s Day) Flood occurred prior to the construction of any Corps of Engineers’ flood control dams. The base flow for the Ohio River on March 9 was 50,100 cfs. Water content of the snow in the district was 2” to more than 4” in the mountains. Melting snow and about 0.65 inches of precipitation caused a rise on the 12^{th}-13^{th} at which time the “Point” gage reached 25.8 feet and was above flood stage for 21 hours. Essentially all snow was melted at this time. Although the flow receded to 99,300 cfs on the 16^{th}, anywhere from 2.5” to 5” of rain fell on the 16^{th} and 17^{th}, with the heaviest in the Lower Allegheny basin. This sent the Ohio River at Pittsburgh to a crest of 46 feet (740.2 feet above NGVD and 557,000 cfs), the river remained above flood stage for 84 hours. It would have been reduced by 10.7 feet with the present reservoir system. A third rise occurred on the 25^{th}-26^{th} during which the river was above flood stage for 32 hours, cresting at 30.6 feet. Total runoff for the month of March 1936 was 8.74 inches at Pittsburgh.

The June 23, 1972 Flood, a result of Tropical Storm Agnes, produced the highest stage at the Pittsburgh “Point” using the current reservoir system. The Ohio River flow on June 20^{th} was 23,700 cfs at the "Point". From the 20^{th} through the 26^{th}, the Allegheny Basin received from 4” to 12” of rainfall and the Monongahela Basin from less than 3” to over 12”. The Ohio River crested at Pittsburgh at 35.85 feet (730.0 feet above NGVD and 380,000 cfs), remaining above flood stage for 86 hours. It would have been 12.1 feet higher without the current reservoir system. The runoff during the flood at Pittsburgh was 4.65 inches for the period June 21-July 15, 1972.

Table 3.2.3-1 presents peak water surface elevations for historic high water events, including the March 1936 and June 1972 floods at the Pittsburgh “Point” and Wheeling, WV.

Table 3.2.3-1 Historical Peak Elevation Events on the Ohio River in the Pittsburgh District

Virginia	Pittsburgh (Point), Pennsylvania	Wheeling, West
	Elevations in feet above NGVD	
March 18, 1936	740.2	666.0
December 31, 1942	730.8	662.3
June 24, 1972	730.0	657.4
April 27, 1937	729.3	656.7
January 20, 1996	728.8	654.2

Historical profiles and the way they are presented may vary from district to district. Various other information such as communities, major roads, major tributaries, etc are also shown. The historical flood profile elevations would be reduced, but to a varying degree by the new reservoirs constructed after the occurrence of the flood. All three districts have plots of historical and frequency profiles in their office files. Examples of both types of profiles are presented in the J. T. Myers Engineering Site Appendix (ED-1) for the reach near the project.

In the Louisville District, the April 1976 discharges for the Ohio River were the basis of the frequency profiles that were developed for the Ohio River. The factors used to develop the HEC-2 model were verified by the reproduction of historical flood profiles utilizing the April 1976 ORD stage and discharge frequency curves.

3.2.4 Natural and Existing Flood Flows

Stage data that is obtained at the recording locations do not provide a homogeneous set of data. The operation of the flood control dams upstream results in a set of data that is existing at that particular time. To obtain a natural condition, water stored for a selected time interval in each reservoir must be routed downstream and added to the appropriate gage. This would have the effect of raising the gage heights and making flood profiles higher. To obtain the present condition at a particular gage, the opposite process is required. All reservoirs that were not built or operated differently must have flows adjusted at the dam by its normal operation. The water that would have been stored for a selected time period is routed downstream and subtracted from the appropriate gage. This has the effect of lowering stages and lowering the flood profile.

Flood flows are difficult to determine for a stream the length of the Ohio River. If another reservoir project is built or an operation is changed, the modified condition will change (probably minimally). The Lakes and River Division, known as the Ohio River Division at the time of the study, using the methodology described above for all of the reservoirs in the Ohio River Basin developed discharge frequency flow curves for a number of locations. The data was labeled "19__ modified conditions. However, the division used only the annual peak at each gage in developing frequency flow data. This has little effect on floods occurring less than once in ten years. However, these curves did not include partial, multiple yearly peaks in the statistical analysis.

3.2.5 Stage and/or Discharge Frequency Relationships

The Corps of Engineers Great Lakes and Ohio River Division (successor to the Ohio River Division, or "ORD") periodically provided to each district bordering the Ohio River, natural and modified (reflecting reductions attributable to upstream lake projects) stage and discharge-frequency curves at a number of gage locations along the river. The updates resulted from additional lake projects being added. The last set provided were dated April 1976. Projects added since that date have minimal effects on the data, these curves are considered current. An example of one location is at the Evansville gage (river mile 792.3) (**Figure 3.2.5-1)** where curves with stage and discharge values are shown for various frequency of occurrence. These curves were based on maximum annual peaks only and did not include partial, multiple yearly peaks in the statistical analysis.

It was known that the April 1976 curves were basically correct for the 10% chance exceedence flood frequency (commonly known as the 10-year flood) and less frequent floods. In the Louisville District, since there was not a gage at the location of the present Myers Dam project before it was built (construction started in 1970 and completed in 1975), the period-of-record was not long enough at that time to properly analyze discharges and stages for more frequent flood events. This may occur at other projects where lock expansions are planned.

Within the last year, an analysis has been made to compare actual peaks that have occurred since the present pools were established and compare the results to the 1976 Ohio River curves developed in the Division Office. Of special concern was the plotting of the partial duration portion of the curve so that elevations of the more frequent occurrence floods could be better estimated. At the Evansville gage, the partial peaks for the 29-year period (1970-1998) were plotted versus the Ohio River Division curve data, as shown in **Figure 3.2.5-1**. The stage-frequency curve and discharge-frequency curve for the Evansville gage are shown as **Figures 3.2.5-2** and **3.2.5-3** respectively and includes the blending of the annual events with partial duration data. Partial duration stage data has been plotted, with results from the HEC-2 model study for the Ohio River at J. T. Myers site, since data has been collected. These results are shown for the upper gage and lower gage in **Figures 3.2.5-4** and **3.2.5-5** respectively.

The analyses that have been made within the last year have been forwarded to the Division Office for review and concurrence. Ohio River data in the Louisville District, developed by the Division Office in 1976, generally provide smooth transitions when plotted with the partial duration data for locations above the Wabash River.

Figure 3.2.5-1

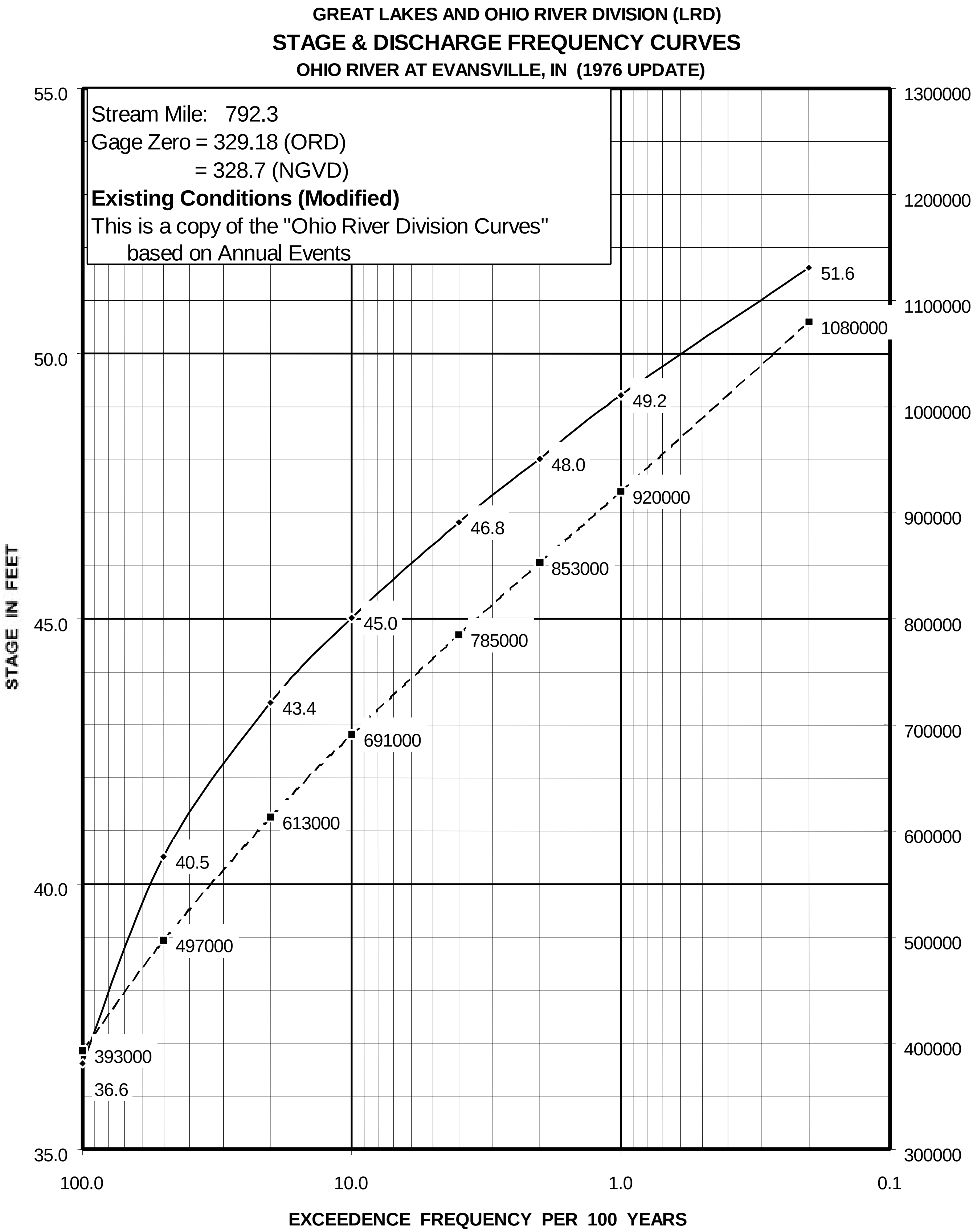

GREAT LAKES AND OHIO RIVER DIVISION (LRD)
STAGE & DISCHARGE FREQUENCY CURVES
OHIO RIVER AT EVANSVILLE, IN (1976 UPDATE)
Stream Mile: 792.3
Gage Zero = 329.18 (ORD)
= 328.7 (NGVD)
Existing Conditions (Modified)
This is a copy of the "Ohio River Division Curves"
based on Annual Events
STAGE IN FEET
EXCEEDENCE FREQUENCY PER 100 YEARS
55.0
50.0
45.0
40.0
35.0
1300000
1200000
1100000
1000000
900000
800000
700000
600000
500000
400000
300000
100.0
10.0
1.0
0.1
51.6
1080000
49.2
48.0
920000
46.8
853000
45.0
785000
43.4
691000
613000
40.5
497000
393000
36.6

Figure 3.2.5-2

STAGE FREQUENCY CURVE

OHIO RIVER AT EVANSVILLE, IND.

(Comparison of 1976 with 1998 Update)

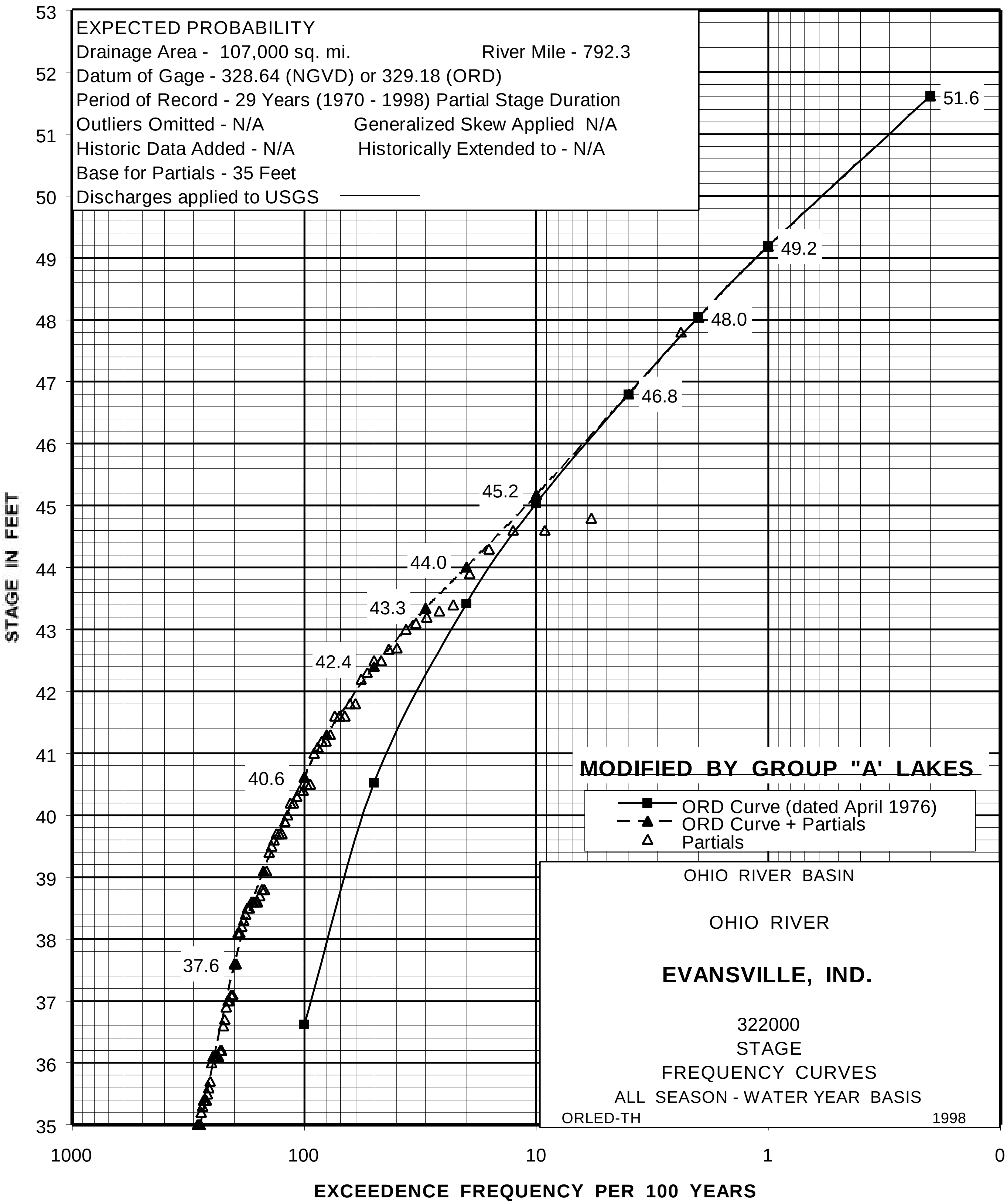


Figure 3.2.5-3

DISCHARGE FREQUENCY CURVE

OHIO RIVER AT EVANSVILLE, IND.

(Comparison of 1976 with 1998 Update)

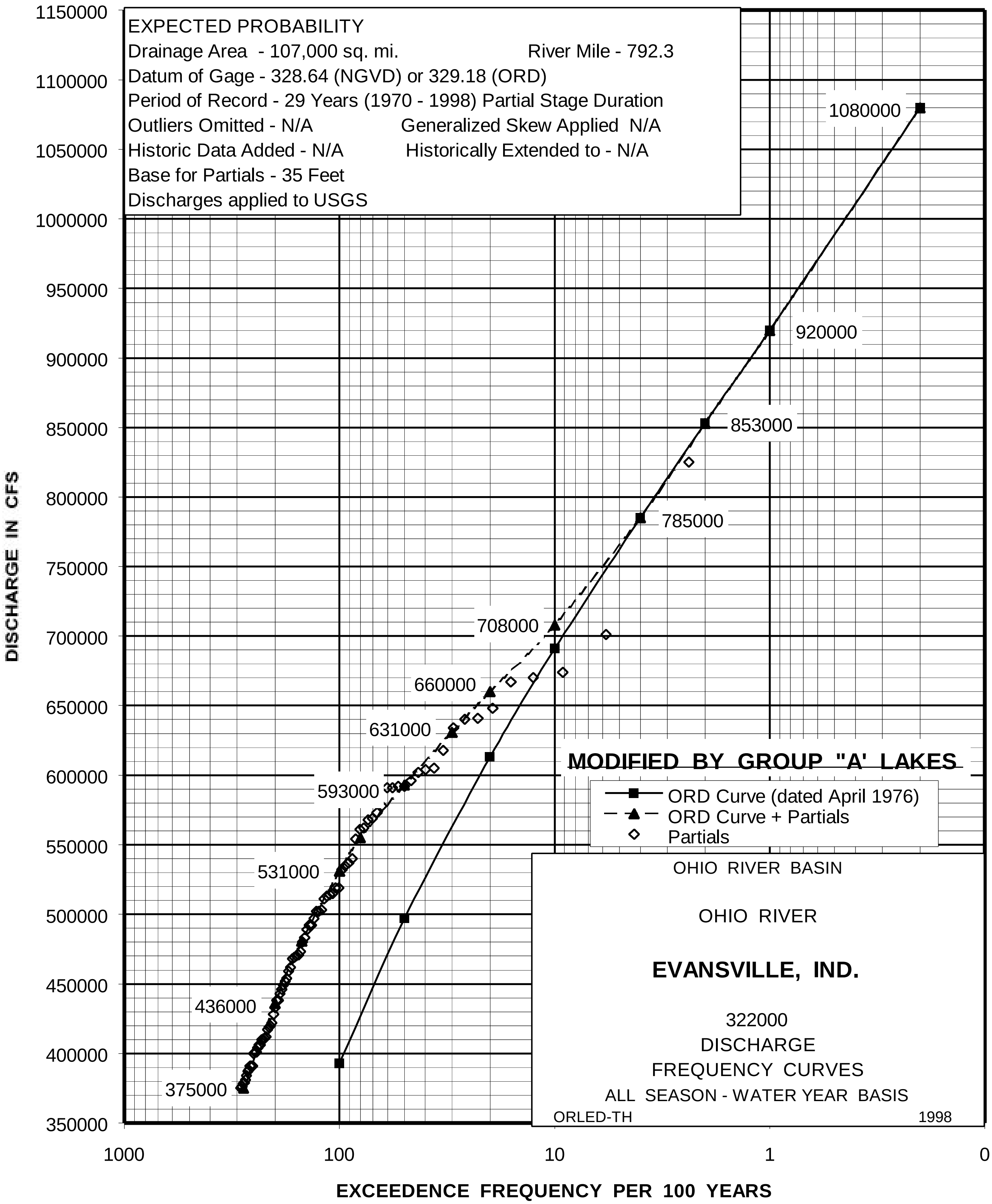


Figure 3.2.5-4

STAGE FREQUENCY CURVE
OHIO RIVER AT T. J. MYERS L & D - UPPER GAGE
(UNIONTOWN L & D)

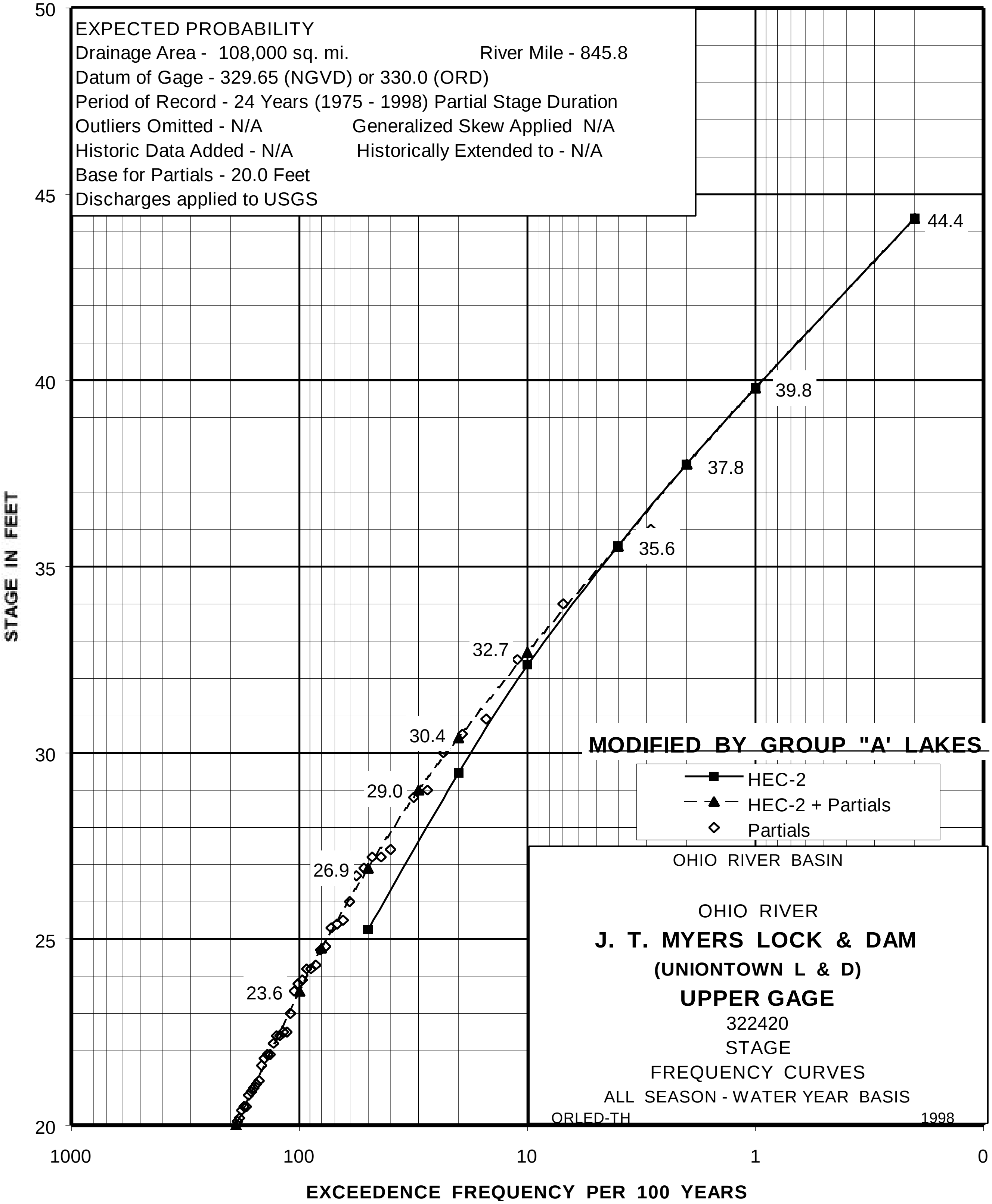
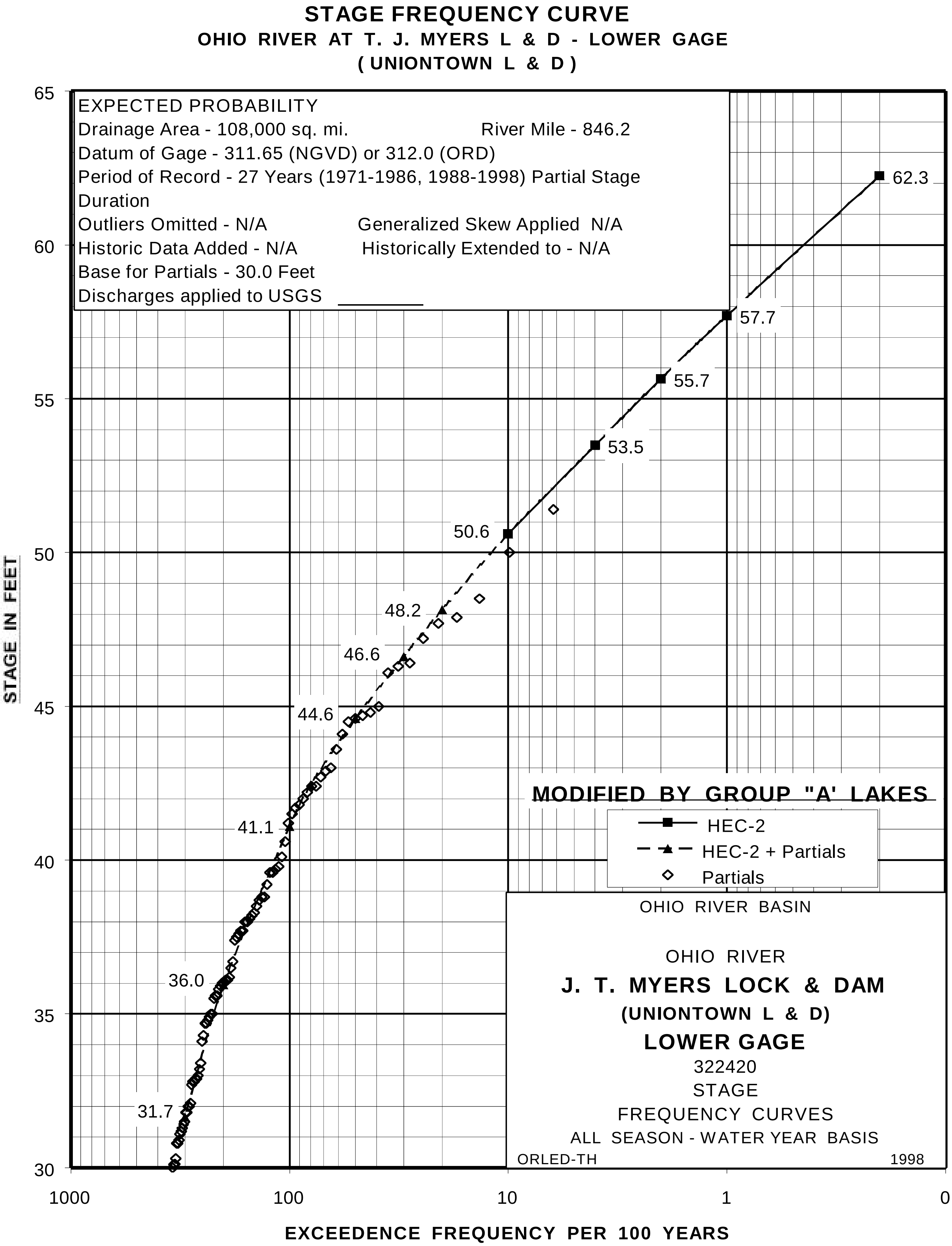


Figure 3.2.5-5


STAGE FREQUENCY CURVE
OHIO RIVER AT T. J. MYERS L & D - LOWER GAGE
(UNIONTOWN L & D)
EXPECTED PROBABILITY
Drainage Area - 108,000 sq. mi.
River Mile - 846.2
Datum of Gage - 311.65 (NGVD) or 312.0 (ORD)
Period of Record - 27 Years (1971-1986, 1988-1998) Partial Stage Duration
Outliers Omitted - N/A
Generalized Skew Applied N/A
Historic Data Added - N/A
Historically Extended to - N/A
Base for Partials - 30.0 Feet
Discharges applied to USGS
62.3
57.7
55.7
53.5
50.6
48.2
46.6
44.6
41.1
36.0
31.7
MODIFIED BY GROUP "A' LAKES
HEC-2
HEC-2 + Partials
Partials
OHIO RIVER BASIN
OHIO RIVER
J. T. MYERS LOCK & DAM
(UNIONTOWN L & D)
LOWER GAGE
322420
STAGE
FREQUENCY CURVES
ALL SEASON - WATER YEAR BASIS
ORLED-TH
1998
STAGE IN FEET
65
60
55
50
45
40
35
30
1000
100
10
1
0
EXCEEDENCE FREQUENCY PER 100 YEARS

In Pittsburgh District studies, the natural discharge frequency flows were developed using 118 years of record (1855-1972) for the Ohio River at Pittsburgh. Floods that occurred during and after the construction of the current reservoir system were adjusted to reflect natural peak discharges that would have occurred without the flood reduction dams. The natural frequency thus obtained was subsequently adjusted for the reduction of the current reservoir system as applicable to produce a reduced discharge frequency. At Montgomery, New Cumberland, Pike Island and Hannibal Locks and Dams, records kept since the dams began operating were used in the frequency determination. These records were based on long term estimates from the existing Dashields Locks and Dam and Lock and Dam 12 which was removed 1975. The Ohio River 10-year through 500-year frequencies were adjusted in agreement with Corps of Engineers Ohio River Division in 1976. **Table 3.2.5-1** presents stage and flow frequency values at the locks and dams. Plates presenting stage frequency curves at the locks and dams are available in the Pittsburgh District.

Table 3.2.5-1 Stage and Flow Frequency Values on the Ohio River at Pittsburgh District's Locks and Dams

Recurrence Interval	Emsworth			Dashields		
	Flow	UG	LG	Flow	UG	LG
10	282,000	716.2	713.2	282,000	707.4	705.2
50	362,000	720.4	718.2	362,000	712.2	711.1
100	394,000	722.0	720.3	394,000	714.1	713.1
500	480,000	726.7	725.4	480,000	719.2	718.6

Recurrence Interval	Montgomery			New Cumberland		
	Flow	UG	LG	Flow	UG	LG
10	314,000	691.5	690.0	299,000	672.2	671.3
50	392,000	696.8	695.6	375,000	677.7	676.8
100	424,000	698.7	697.6	411,000	680.1	679.2
500	502,000	703.6	702.5	485,000	684.85	683.9

Recurrence Interval	Pike Island			Hannibal		
	Flow	UG	LG	Flow	UG	LG
10	300,000	654.0	652.8	283,000	629.0	628.0
50	375,000	660.1	659.3	360,000	635.0	634.2
100	406,000	662.5	661.8	398,000	637.7	637.0
500	470,000	666.9	666.4	440,000	640.5	639.9

Note: UG = Upper Gage, LG = Lower Gage

The Ohio River flow frequencies for less than the 10-year flood in the Pittsburgh District, were developed for the period 1966 to 1997, which is after the construction of the Allegheny

Reservoir and Kinzua Dam project. The Ohio River at Dashields flow records were used to compute the actual and reduced discharge frequency. The Ohio River frequencies were related to the Dashields frequency using the same proportions that the 1976 frequencies were related to Pittsburgh frequency. From the stage and streamflow data, stage-discharge relationships have been developed for all of the existing navigation dams and at other points on this reach of the river.

3.2.6 Ordinary High Water

Ordinary High Water (OHW) is a line on the bank of a river or other body of water that marks the boundary of those lands subject to navigational servitude. The public has the right to navigate freely over lands subject to navigational servitude. Also, physical facilities intended to support navigation may be placed and maintained on such lands.

The line of ordinary high water, as applied to rivers, that separates what properly belongs to the riverbed from that which belongs to the owner of adjacent land is determined by normal conditions, not by reference to unusual floods. Ordinary high water is the point on the bank where the waters are so continuous as to leave a distinct mark either by erosion, destruction or terrestrial vegetation, or other easily recognized characteristics. The most common method of identifying OHW marks is to find that elevation on the bank below which terrestrial (dry land) vegetation does not exist. Other indicators are: (1) absence of commercial agriculture, (2) drift or debris lines, (3) changes in soil characteristics, (4) benching and shelving of the bank, (5) absence of all vegetation, and (6) absence of commercial human activity.

The ordinary highwater elevation not only has an effect on the adjacent environment but also is critical on the Ohio River with relation to water supply inlets, storm and sanitary sewer outlets, permanent and floating docks, and adjacent industrial, residential and recreational facilities. The extension of present locks or the addition of a third lock would not have an effect on the ordinary highwater profile. Therefore this is of little concern in the Huntington and Louisville Districts in this study. Ordinary highwater profiles for the Ohio River are available in both districts.

There is a possibility that a study of replacing the upper three locks and dams near Pittsburgh with two locks and dams would need evaluation. This would change the ordinary highwater profile in these reaches. The Pittsburgh District is currently reevaluating Ordinary High Water for their District's six navigational pools. The 0.7 year frequency profile is estimated to be the District's Ordinary High Water for the Ohio River. Ongoing field investigations will better define the District's current Ordinary High Water line. This updated profile together with the standard project flood, the 100-year flood, the streambed, and the normal pool level resulting from the Ohio River dams, are available from the Pittsburgh district.

3.2.7 Low Flow Conditions

Low flow conditions will normally be an asset during lock expansion construction. The months when low flows can be expected are available through the gage's history or from continuous gage records. As an example, in the Pittsburgh District, the most sustained and severe period of low flow in the Ohio River occurred during the summer and autumn of 1930. The actual average flow at Pittsburgh in October 1930 dropped to 1,206 cfs. It is estimated that the October flow would have been even lower, about 900 cfs, if Lake Lynn on the Cheat River had not released water reserved for power generation. Low flow augmentation by existing reservoirs would have greatly improved these conditions. **Table 3.2.7-1** shows the mean monthly actual, natural and augmented 1930 drought flows on the Ohio River at Pittsburgh, Pennsylvania. Also included in **Table 3.2.7-1** are the mean monthly flows from the more recent droughts of 1988 and 1991 obtained from the U.S. Geological Survey Water Resources Data publication for the Ohio River at Sewickley, Pennsylvania.

Table 3.2.7-1
Monthly Mean Flows
Ohio River at Pittsburgh, Pennsylvania
(Flow in cfs)

	Jul	Aug	Sep	Oct	Nov	Dec
1930 Drought						
Actual	3,979	1,284	1,273	1,206	1,563	6,643
Natural *	3,951	1,241	1,000	903	1,394	6,737
Augmented - Existing	5,708	4,205	4,186	4,156	3,740	6,712
1988 Drought	6,308	5,076	9,241	18,470	19,830	51,490
1991 Drought	6,263	4,953	5,132	49,600	31,670	74,740

***** Without Lake Lynn Drawdown

The seven day - ten year frequency flow (Q7-10) is defined as a mean low flow for seven consecutive days that will recur, on the average, once in ten years. The Q7-10 flows were developed for the Ohio River based on 31 years of record for the period 1949 to 1979. **Table 3.2.7-2** shows the Ohio River at selected points in the Pittsburgh District of the Q7-10 flows which were based on regulated conditions by the upstream reservoirs.

Table 3.2.7-2
Seven Day - Ten Year Flow (Q7-10)

Ohio River Location	Flow in cfs
Dashields Locks and Dam	4,800
Montgomery Locks and Dam	5,700
New Cumberland Locks and Dam	5,750
Pike Island Locks and Dam	5,830
Hannibal Locks and Dam	5,850

3.2.8 Pool Hydrographs and Stage Duration

Previous paragraphs have addressed historical and frequency floods and profiles as well as low flow information. Equally important are pool hydrographs and duration data.

In the Louisville District, data can be obtained from each of the stations shown in **Table 3.2.2-3** to provide a wide range of information. In the John T. Myers Appendix (ED-1), daily 7 a.m. gage readings were obtained from Codes 401 and 402 to produce a comparison of daily upper and lower pool elevations at J.T. Myers Locks and Dam for the period of record**. Figure 3.2.8-1** is an example for water year 1976. Pool hydrographs differ from the stage duration data. Hydrographs indicate the number of times an elevation is attained during a certain period of time whereas duration data show the number of days or percent of time an elevation is attained.

Stage duration data provides information concerning the number of days or percent of time that a particular elevation is equaled or exceeded. This information is provided by a particular month or annually for the period of record shown. **Tables 3.2.8-1** and **3.2.8-2** show the number of days and percent of time a particular pool elevation is equaled or exceeded in J. T. Myers lower pool. **Figure 3.2.8-2** shows the data in graphical form for the tabular data for the lower pool.

To better pinpoint the time to accomplish certain construction activities, **Figures 3.2.8-3** and **3.2.8-4** show the maximum elevation, the average for the 24 years of data for calendar year 1975 through 1998, and the minimum elevation for each date in the calendar year. **Figure 3.2.8-3** shows the difference between a controlled upper pool versus the fluctuating uncontrolled lower pool (**Figure 3.2.8-4**).

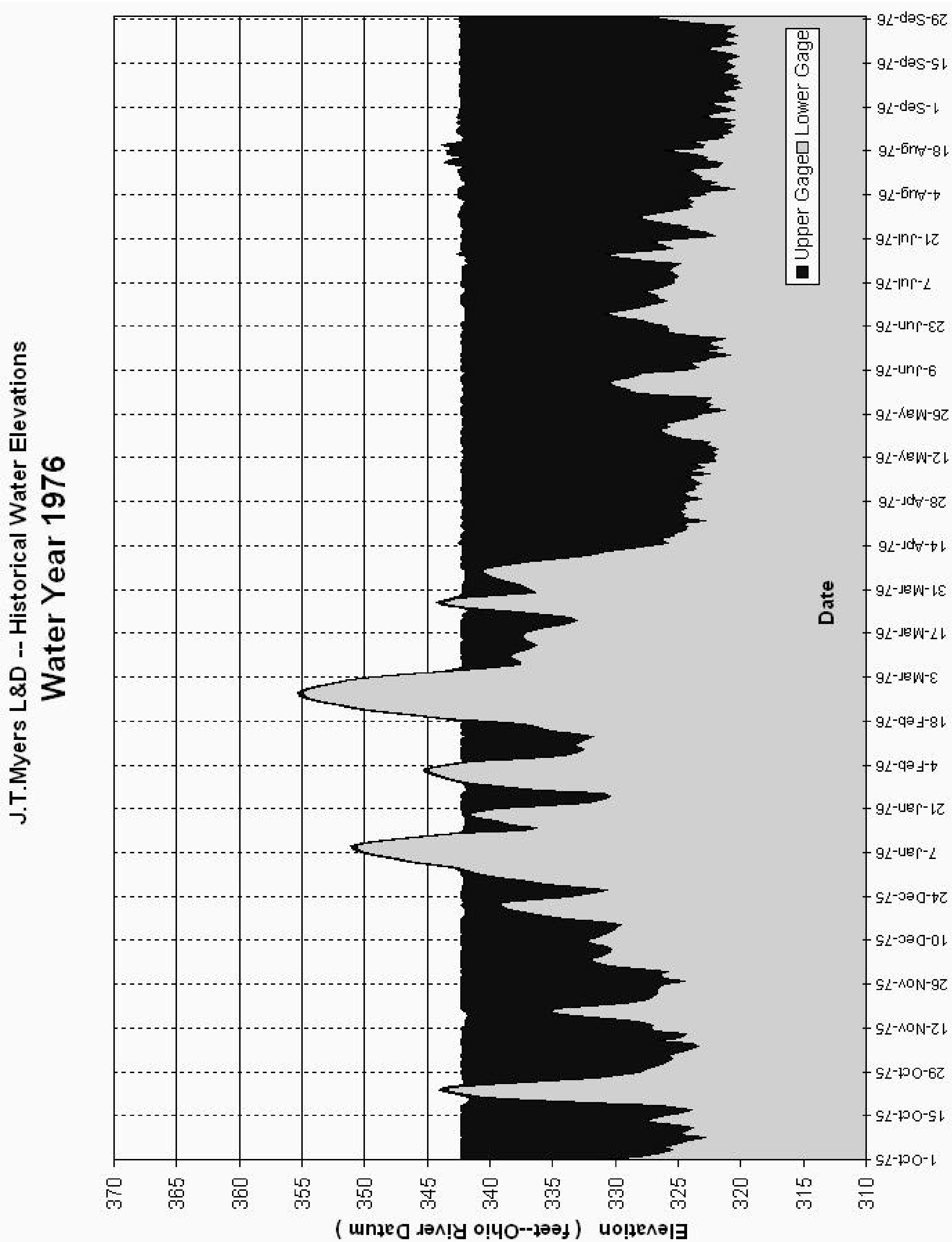

J.T.Myers L&D -- Historical Water Elevations
Water Year 1976
Elevation (feet--Ohio River Datum)
370
365
360
355
350
345
340
335
330
325
320
315
310
1-Oct-75
15-Oct-75
29-Oct-75
12-Nov-75
26-Nov-75
10-Dec-75
24-Dec-75
7-Jan-76
21-Jan-76
4-Feb-76
18-Feb-76
3-Mar-76
17-Mar-76
31-Mar-76
14-Apr-76
28-Apr-76
12-May-76
26-May-76
9-Jun-76
23-Jun-76
7-Jul-76
21-Jul-76
4-Aug-76
18-Aug-76
1-Sep-76
15-Sep-76
29-Sep-76
Date
Upper Gage
Lower Gage

Figure 3.2.8-1

TABLE 3.2.8-1

OHIO RIVER AT J.T.MYERS (LWR)
ELEVATION DURATION TABLE
FOR PERIOD (OCT 1975 - SEP 1998)

*** NUMBER OF DAYS WHEN ELEVATION IS >= CLASS ***

CLASSES (FEET)	FOR YEAR	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
		FOR MONTHS											
366.00	0	0	0	0	0	0	0	0	0	0	0	0	0
365.00	4	0	0	0	0	0	4	0	0	0	0	0	0
364.00	6	0	0	0	0	0	6	0	0	0	0	0	0
363.00	11	0	0	0	3	0	8	0	0	0	0	0	0
362.00	17	0	0	0	6	0	11	0	0	0	0	0	0
361.00	23	0	0	0	8	0	15	0	0	0	0	0	0
360.00	34	0	0	0	10	0	21	0	3	0	0	0	0
359.00	49	0	0	0	13	0	24	0	12	0	0	0	0
358.00	74	0	0	5	16	0	32	0	21	0	0	0	0
357.00	91	0	0	8	17	0	36	1	29	0	0	0	0
356.00	124	0	0	11	21	13	41	4	34	0	0	0	0
355.00	154	0	0	16	23	20	50	6	39	0	0	0	0
354.00	192	0	0	20	24	31	61	14	42	0	0	0	0
353.00	254	0	0	23	25	36	76	39	55	0	0	0	0
352.00	325	0	0	27	27	48	90	65	68	0	0	0	0
351.00	418	0	0	29	35	57	114	94	88	1	0	0	0
350.00	511	0	0	32	45	78	130	115	100	11	0	0	0
349.00	631	0	2	42	57	99	151	144	113	23	0	0	0
348.00	747	0	6	55	69	127	171	166	120	32	0	0	1
347.00	888	0	13	75	81	158	199	185	128	44	3	0	2
346.00	1025	0	17	85	103	176	231	203	147	56	3	0	4
345.00	1158	0	21	104	113	194	269	221	156	70	5	0	5
344.00	1308	0	24	137	132	207	304	240	171	83	5	0	5
343.00	1458	2	28	160	159	227	335	255	187	91	6	1	7
342.00	1608	4	36	182	185	241	366	278	198	100	7	2	9
341.00	1734	8	41	97	1	251	391	296	08	0	8	4	9
340.00	1885	12	49	216	231	268	417	328	219	116	11	7	11
339.00	2057	16	56	243	249	290	449	356	234	130	13	9	12
338.00	2229	20	66	265	271	310	482	383	245	142	17	15	13
337.00	2398	23	76	286	289	329	501	409	270	161	21	19	14
336.00	2568	33	86	309	311	346	526	428	282	179	28	23	17
335.00	2775	43	102	325	329	369	547	462	311	197	35	33	22
334.00	3011	57	123	342	359	400	572	496	336	214	44	44	24
333.00	3261	72	142	359	388	427	599	526	371	237	60	54	26
332.00	3517	81	167	382	424	471	623	544	391	258	81	63	32
331.00	3787	95	204	415	452	502	633	566	417	282	107	74	40
330.00	4138	113	242	456	488	531	653	599	461	311	141	91	52
329.00	4515	137	286	493	524	553	677	626	506	352	183	116	62
328.00	4998	157	337	545	566	584	697	642	560	403	254	168	85
327.00	5558	205	396	594	612	605	705	664	615	478	346	206	132
326.00	6245	281	490	642	648	618	713	674	653	557	471	297	201
325.00	7159	452	587	678	658	630	713	678	673	608	625	487	370
324.00	7967	653	633	688	672	636	713	688	681	652	684	668	599
323.00	8069	663	648	698	690	638	713	689	690	657	695	679	609
322.00	8202	672	670	705	703	640	713	690	706	667	709	692	635
321.00	8317	686	689	711	712	643	713	690	711	680	713	706	663
320.00	8386	708	690	713	713	647	713	690	713	690	713	713	683
319.00	8398	712	690	713	713	650	713	690	713	690	713	713	688
318.00	8401	713	690	713	713	650	713	690	713	690	713	713	690

TABLE 3.2.8-2

OHIO RIVER AT J.T.MYERS(UPR)
ELEVATION DURATION TABLE
FOR PERIOD (OCT 1975 - SEP 1998)

*** PERCENTAGE OF DAYS WHEN ELEVATION IS >= CLASS ***

CLASSES (FEET)	FOR YEAR	FOR MONTHS OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
367.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
366.00	.04	.00	.00	.00	.00	.00	.42	.00	.00	.00	.00	.00	.00
365.00	.06	.00	.00	.00	.00	.00	.70	.00	.00	.00	.00	.00	.00
364.00	.10	.00	.00	.00	.14	.00	.98	.00	.00	.00	.00	.00	.00
363.00	.17	.00	.00	.00	.70	.00	1.26	.00	.00	.00	.00	.00	.00
362.00	.24	.00	.00	.00	.84	.00	1.96	.00	.00	.00	.00	.00	.00
361.00	.30	.00	.00	.00	1.12	.00	2.38	.00	.00	.00	.00	.00	.00
360.00	.48	.00	.00	.00	1.54	.00	3.09	.00	.98	.00	.00	.00	.00
359.00	.67	.00	.00	.42	2.10	.00	3.51	.00	1.82	.00	.00	.00	.00
358.00	.96	.00	.00	1.12	2.24	.00	4.63	.00	3.37	.00	.00	.00	.00
357.00	1.20	.00	.00	1.40	2.66	.62	5.19	.29	4.07	.00	.00	.00	.00
356.00	1.56	.00	.00	1.82	2.95	2.46	5.89	.58	4.91	.00	.00	.00	.00
355.00	2.04	.00	.00	2.52	3.23	3.85	7.71	1.45	5.61	.00	.00	.00	.00
354.00	2.58	.00	.00	3.09	3.51	5.08	9.40	3.62	6.31	.00	.00	.00	.00
353.00	3.31	.00	.00	3.51	3.51	6.15	11.22	6.81	8.56	.00	.00	.00	.00
352.00	4.38	.00	.00	3.93	4.49	8.00	14.59	10.87	10.80	.00	.00	.00	.00
351.00	5.46	.00	.00	4.21	6.03	9.85	17.25	15.07	13.04	.29	.00	.00	.00
350.00	6.64	.00	.00	5.19	7.57	13.23	19.50	18.41	14.31	1.88	.00	.00	.00
349.00	7.89	.00	.29	6.17	8.70	16.15	22.30	22.17	15.85	3.62	.00	.00	.00
348.00	9.45	.00	1.01	8.56	10.10	21.08	25.53	25.51	17.11	4.93	.14	.00	.29
347.00	11.17	.00	2.03	11.22	12.76	25.23	29.45	27.68	19.07	6.67	.42	.00	.43
346.00	12.78	.00	2.61	13.04	14.87	28.31	34.08	30.43	21.18	8.84	.42	.00	.72
345.00	14.53	.00	3.19	16.55	16.69	31.23	39.69	33.04	22.86	10.87	.70	.00	.72
344.00	16.18	.28	3.62	20.76	19.92	33.08	44.04	34.78	24.96	12.32	.70	.00	.72
343.00	22.70	8.27	6.23	26.51	26.51	39.08	50.07	39.71	30.15	18.84	7.71	11.92	8.26
342.00	98.61	98.60	99.13	98.18	97.76	98.31	98.32	98.55	99.30	98.55	98.18	98.88	99.57
341.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

FIGURE 3.2.8-2 OHIO RIVER AT J. T. MYERS (LOWER) FOR YEAR ELEVATION DURATION CURVE FOR PERIOD (OCT 1975 - SEP 1998)

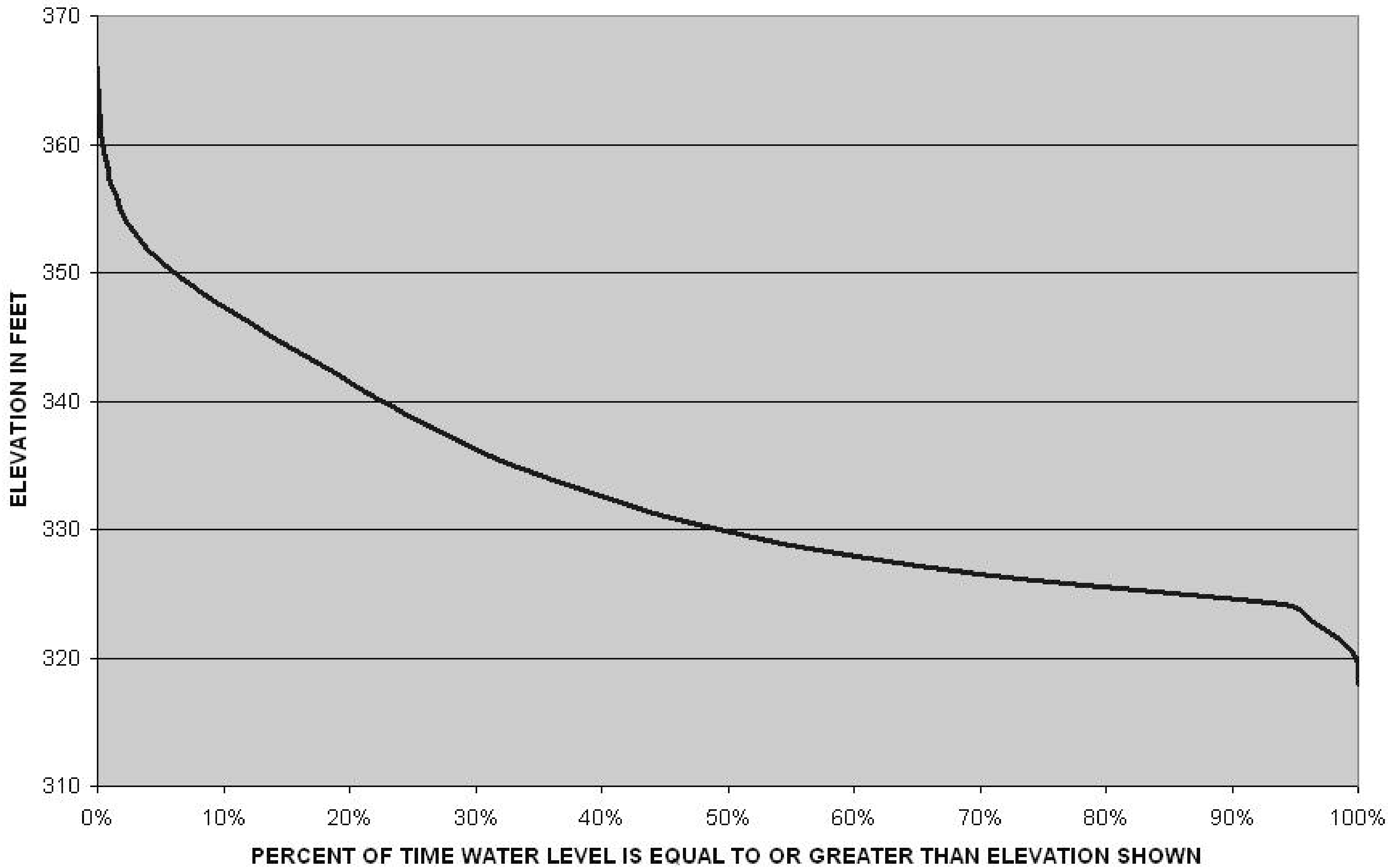


FIGURE 3.2.8-3

J.T. Myers L&D Upper Gage (Jan75-Dec98)

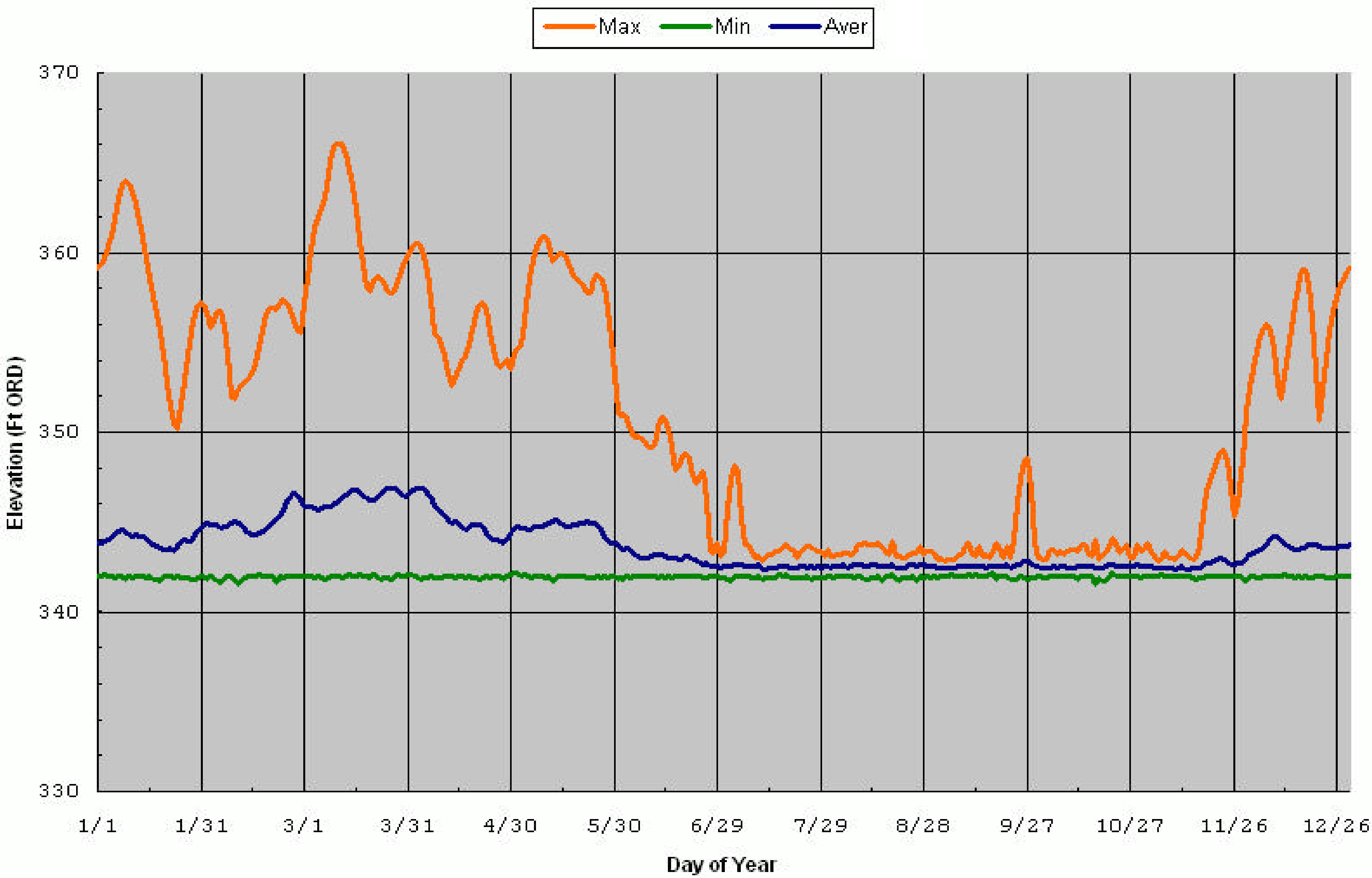
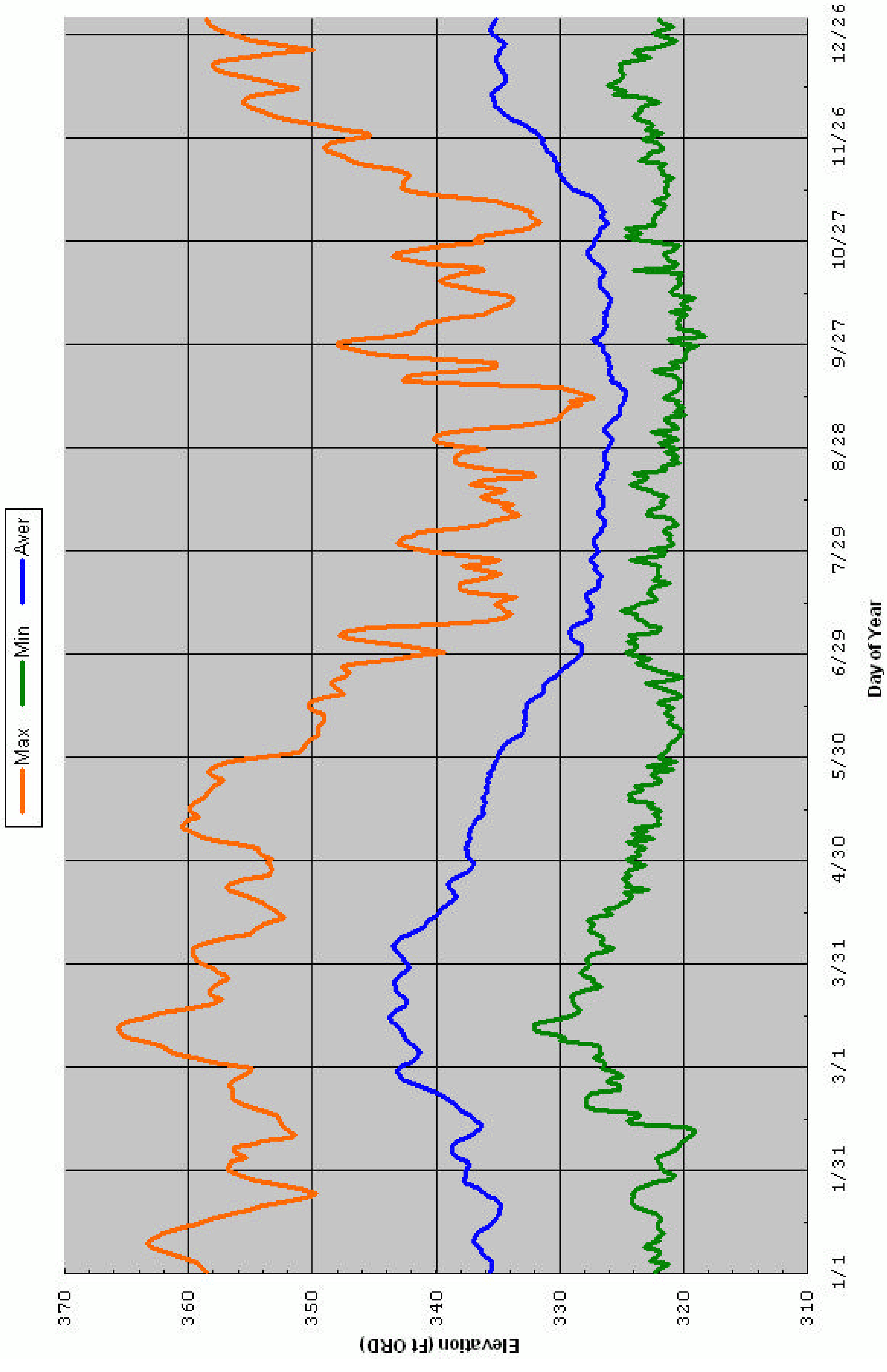


FIGURE 3.2.8-4

J.T. Myers L&D Lower Gage (Jan75-Dec98)



3.3 LOCK DESIGN HYDRAULICS (TYPICAL FOR OHIO RIVER)

3.3.1 Approach Conditions

Before a vessel can successfully enter the lock chamber, it must first approach the lock over open water. The approach conditions are typically evaluated with physical hydraulic models to be sure that adverse currents do not occur. In some cases, it may be necessary to construct underwater dikes to modify the currents to provide for safe approach conditions. Final approach to the lock chamber is aided by the presence of lock approach walls both upstream and downstream of the locks. Vessels arriving at the lock will use the approach wall to align themselves properly for entry into the lock. In terms of safety and processing time, the approach characteristics of a lock are one of the most important features of the navigation projects on the Ohio River.

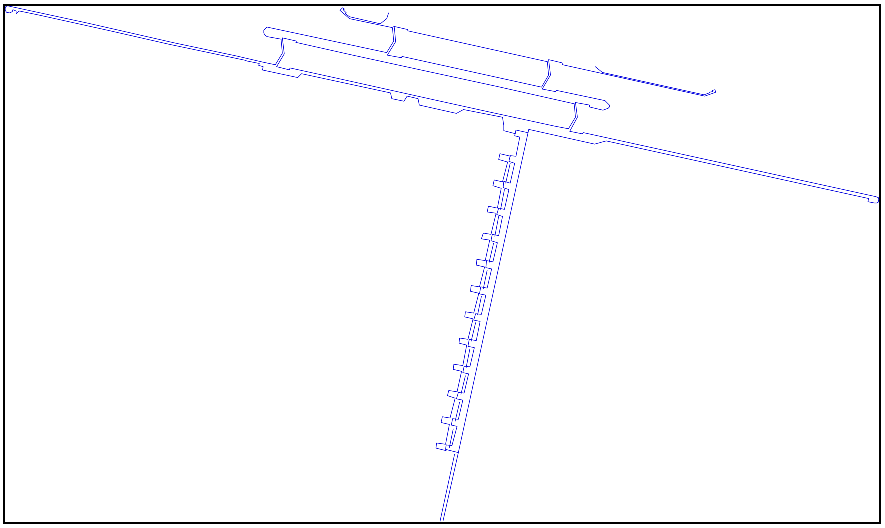
Approach Walls

Vessels entering or exiting a lock at low speed lack maneuverability and steerageway and are susceptible to adverse currents. Approach walls are used to safely guide vessels and tows into or out of the lock chamber. They also provide a mooring location for long tows that require multiple lockages. An additional benefit provided by some of the walls is protection from hazardous areas and adverse currents.

Typical Arrangement

For navigation projects on the Ohio River, the two typical types of approach walls are the guide and guard walls. The distinguishing feature between the two types is their position with respect to the dam. Guard walls are located between the locks and the discharging portion of the dam. The wall situated on the landward side of the lock approach is defined as the guide wall. Approach walls are further subdivided based on their location either upstream (upper) of downstream (lower) of the dam axis. Of the twenty active locks and dam on the Ohio River, thirteen have approach wall configurations as provided in ***Figure 3.3.1A***.

FIGURE 3.3.1A Approach Wall Configurations



Upper Guard Wall

Downbound tows aligning for entry into the lock chamber utilize this wall. The ports typically found in this wall allow currents in the upstream approach to pass under the wall and flow towards the dam. These currents tend to hold tows against the wall, thus facilitating safe entry into the lock. Without the ports, lateral currents across the upper approach would tend to push tows towards the bullnose. The wall is configured so that the largest tows can safely align themselves for entry into the lock chamber.

Upper Guide Wall

This wall is typically used as an alignment wall for the auxiliary lock chamber. Because most of the auxiliary locks are only 600 feet long, the length of these walls is typically less than the upper guard wall. In general, vessels and tows using this wall are not adversely affected by river currents. Tows that are longer than the wall, however, may have difficulty with alignment due to the currents in the upper approach.

Lower Guard Wall

Upbound tows align for entry into the main lock chamber using this wall. It also protects against adverse currents caused by discharges from the dam. Since currents introduced through this wall would tend to push tows away from the wall, they are not ported. Downstream of the lock approach, the wall induces a slackwater "shadow" that facilitates a safer entry into the lock.

Lower Guide Wall

The typical lock configuration on the Ohio River provides a relatively short landward wall downstream of the auxiliary lock. This wall can be used to align for entry into the auxiliary lock. The middle wall serves as a landing area for upbound vessels.

Unique Approach Conditions

Several of the locks and dams on the Ohio River have approach conditions that warrant a separate discussion.

Smithland and Olmsted

A safe approach wall configuration for twin 1200 feet by 110 feet locks was developed using the physical hydraulic model tests of Smithland. The system consists of a relatively long ported guard wall and a ported middle wall. The middle wall serves as a landing surface and an alignment mechanism for downbound tows. The lower approach walls consist of a non-ported guard wall and a relatively short guide wall. This configuration allows for safe and efficient use of both lock chambers. The approach walls at Olmsted will have the same arrangement.

Emsworth, Dashields, and Montgomery

Since the main lock at each of these projects is only 600 feet long, a standard size Ohio River tow requires multiple lockages. With auxiliary locks measuring 360 feet by 56 feet, significant delays are experienced when the main lock is closed for maintenance purposes.

McAlpine

There are several unique conditions associated with the McAlpine approaches that are not experienced elsewhere in the navigation system. The approach to the canal is very close the downtown Louisville, KY area and leave little room for error. A relatively new vane dike has improved these entry conditions. In addition to the entry conditions, the presence of a railroad bridge with minimal vertical and horizontal clearances make this approach one of the most challenging in the system. In the lower approach, the guard wall is ported to alleviate adverse currents around the bullnose. Occasionally this presents a problem to upbound tows that may be pushed away from the wall. The most serious concern in the lower approach is related to the proposed discharge facilities for the new 1200 foot lock. The lock will discharge directly into the lower approach. As a result, traffic in the lower approach will be severely restricted during periods of discharge.

The action of filling the locks with water from the canal tends to induce long period surges. The period of the surges is typically thirty minutes with a magnitude of one foot. The surges and currents that they generate are such that they can interfere with the operation of the main lock. Filling operations must be performed with great caution to minimize the impact of these surges.

R C Byrd

The project consists of a 1200 foot main lock and a 600 foot auxiliary lock. Similar to McAlpine, the approach to the locks is via a canal. Since the lock intakes are located in an embayment off of the river, the surges experienced at McAlpine are not a problem here. The unique footprint of the locks means that site specific plans must be developed for any capacity enhancement project.

Approach Time

The interval between the time a tow passes the lock arrival point and the time the two is prepared to enter the lock chamber is defined as the approach time. Traffic between the arrival point and the lock chamber is typically limited to one tow. This provides pilots with the maximum flexibility to maneuver and ensures safe utilization of the lock. The approach time can vary depending on the conditions at the lock with the average falling between thirty and forty minutes.

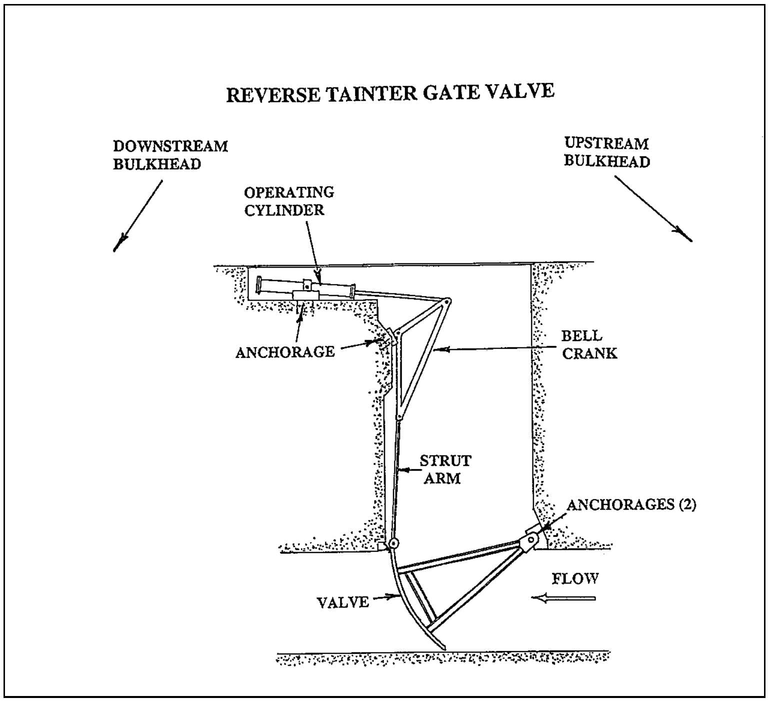
3.3.2 Valves

Each culvert in a F/E system has two valves. The filling valve is located between the upper pool and the lock chamber and the emptying valve is located between the lock chamber and the lower pool. The valves are always the same size and are only operated together during flushing operations. The two filling (or emptying) valves must be synchronized in F/E systems that utilize two culverts. All of the locks constructed since the opening of New Cumberland in 1959 use reverse tainter valves. Some of the locks on the upper reach of the river use butterfly valves. The stoney valve has been used on tributary streams and may be used in applications now under consideration for the enhancement of the Ohio River Navigation System.

Reverse Tainter

The most common valve type in use at Ohio River Navigation Projects is the reverse tainter valve. The valve is a circular arc that is supported by two strut arms that are attached to anchorages via hinges. The valve requires a significant amount of space and is usually place in an open pit within the lock wall. This pit serves as a surge tank during filling and emptying operations. The valves can be operated by cables connected to horizontal hydraulic cylinders, but the most common mechanism consists of a strut arm connected to a hydraulic cylinder through a bell crank assembly. The typical configuration is shown in Figure 3.3.2A. The geometry of the operating mechanism results in a nonlinear relationship between hydraulic cylinder movement and valve opening. This characteristic proves to be beneficial during the early stages of filling or emptying when the discharge rate is changing rapidly.

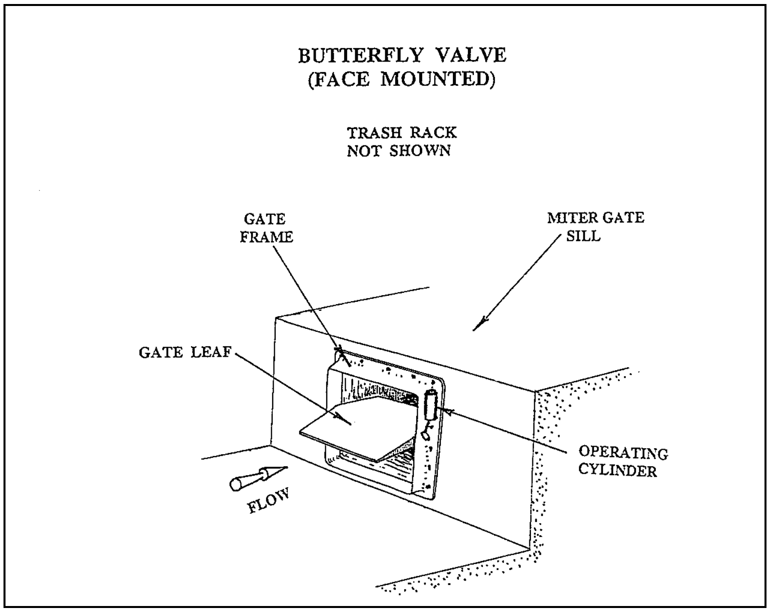
FIGURE 3.3.2A



Butterfly

When combined with a central culvert F/E system, the butterfly valve provides a cost effective means of flow control. The major disadvantage of this valve is associated with anticipated maintenance difficulties. A diagram of this type of valve is provided in Figure.3.3.2B.

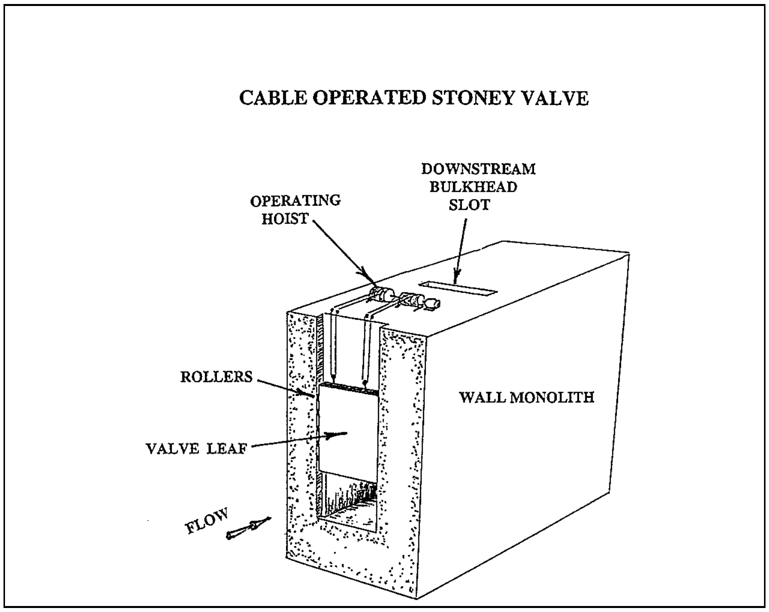
FIGURE 3.3.2B



Stoney

These vertical lift gates can be operated by hydraulic cylinders or hoists. Rollers on either side of the valve run in vertical raceways to reduce frictional forces. Ease of maintenance is achieved by locating the operating mechanism on the top of the lock wall. Another significant advantage is the smaller footprint that is required for the valve. The valve requires less space and the monolith required to support this type of valve is smaller. The operating scheme usually results in a linear valve opening. Careful consideration must be given to any design that incorporates this type of valve with a reverse tainter valve. A typical stoney valve is shown in Figure 3.3.2C.

FIGURE 3.3.2C



3.3.3 Discharge Systems

Velocities near lock discharges are relatively high and the water surface tends to be violent. The outfalls are usually located riverward of the lock chamber so that the turbulent discharges do not interfere with navigation. The lower guard wall protects vessels and tows from the adverse currents and high velocities that are generated during lock discharges. Some of the locks in the inland waterways system have F/E systems that discharge into the lower approach area immediately downstream of the lock. This type of design places restrictions on tow movements in the lower approach, especially when the lock is discharging.

3.3.4 Howser Force

When filling or emptying a lock chamber, small oscillations develop in the water surface within the lock chamber. The oscillations will tend to induce motion in a tow within the lock chamber. As a result, the tow must be moored with hawser lines to prevent it from striking the miter gates. These lines must be able to resist the forces generated by the moving tow. The resisting forces generated in the line are defined as hawser forces. These forces are usually evaluated with physical hydraulic models. Experience has indicated that limiting the hawser forces in a model to less than five tons will provide satisfactory prototype performance. Recent advances in numerical modeling techniques have provided additional methods for evaluating hawser forces. The numerical techniques provide satisfactory results for screening of alternatives, but final design should be based on the results of physical hydraulic model tests.

In traditional F/E systems, the filling cycle will generate greater hawser forces than the emptying cycle. In addition, the most significant factor influencing the oscillations in the lock chamber is the rate of change of discharge (dq/dt). These factors produce the greatest hawser forces during the early part of the filling cycle while the valve is opening.

3.3.5 Chamber Empty / Fill Time

The system of intakes, culverts, valves, ports, and manifolds that is used to raise or lower the water level in the lock chamber is known as the lock filling and emptying (F/E) system. The design of these systems must optimize the solution of two mutually exclusive objectives. The lock must be filled or emptied as rapidly as possible without creating adverse oscillations in the lock chamber.

Typical F/E Systems

The three typical F/E systems used on the Ohio River are: side port, split lateral, and bottom lateral. These designs have been developed to accommodate various combinations of lock size and lift.

Side Port

This system is commonly found in locks with lifts less than twenty five feet. The configuration features a large culvert in each of the lock walls. Intake manifolds are located in the face of the approach walls at a point upstream of the miter gates. Large valves located near the miter gate pintle control flow from the upper pool into the culverts. The culverts are connected to the lock chamber through a series of ports in along the face of the lock chamber wall. The valves that control emptying of the lock chamber are` located downstream of the ports. The discharge section of the culvert leads from these emptying valves to the lower pool.

Split Lateral

Projects with lifts in excess of thirty feet feature this type of F/E system. This configuration is similar to the side port system in that a large culvert is located in each lock wall. The filling valves are also typically located near the miter gate pintle. Instead of ports, each culvert is connected to the lock chamber through a series of lateral culverts. One culvert supplies the lateral field in the upper portion of the chamber and the other culvert supplies the lateral field in the lower portion. These lateral culverts extend from the main culvert across the lock chamber floor to the opposite lock wall. Each of the lateral culverts has a series of ports that allow flow to enter or exit the lock chamber. The valves that control emptying of the lock chamber are located downstream of the lateral culverts. The discharge section leads form the valve to the lower pool.

Bottom Lateral

The 600 foot auxiliary locks on the Ohio River utilize this system. It is similar to the split lateral system except that there is only one culvert instead of two. Consequently, there is only one lateral field extending across the middle portion of the lock chamber. Since the culvert is the same size as the culverts for the main chamber, the valves and bulkheads are interchangeable. The discharge portion of the auxiliary lock passes underneath the main lock chamber so that it can discharge in the lower pool area away from the approach.

Central Culvert F/E System

Traditional F/E systems incorporate large culverts within the lock walls. New lock designs that incorporate roller compacted concrete and other construction materials and techniques cannot accommodate the culverts within the lock walls. As a result, the traditional F/E systems must be adapted to these new designs. The central culvert F/E system has twin culverts situated on the floor of the lock chamber away from the walls.

3.4 DAM OPERATION

3.4.1 Stair Step

The locks and dams on the Ohio River were designed and operated on the “stair step” principle. The target elevation of the upstream pool is such that a minimum navigation depth of nine feet is provided at all times. The height of the dam gates has been set to meet this requirement. The lower miter gate sills of the locks are set to match the target elevation of the next downstream dam. During periods of low flow, the navigation pools are almost flat. This conditions results in the “stair step” profile as shown in Figure 3.4.1A.

The dam gates of a project are operated such that the target elevation of the upper pool is maintained at the upstream face of the dam. This insures a minimum navigation depth of nine feet upstream of the project. During periods of moderate to high flow, the water surface upstream of each dam will develop a sloping profile starting at the upstream face of the dam and extending upstream to the next dam. As a result, a typical lock and dam on the Ohio River will have a relatively steady upper pool elevation and a fluctuating tailwater elevation.

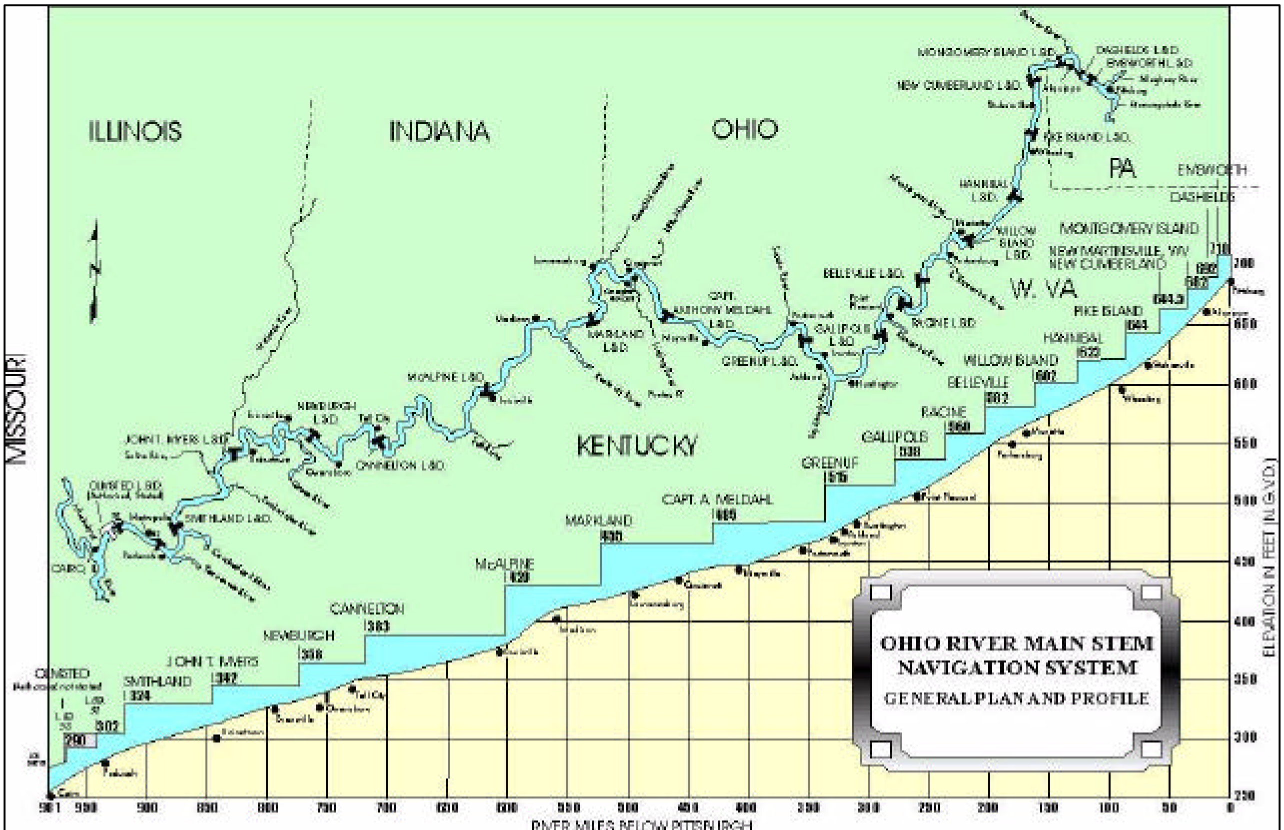


FIGURE 3.4.1A OHIO RIVER PLAN AND PROFILE

If flows in the river increase substantially during a flood, the dam gates can be raised as needed until they are in the fully opened position. Under these conditions, the gates are clear of the water and the upper pool elevation can no longer be controlled. The natural flow of the river then becomes the controlling factor. If the level of the water continues to rise, it is due to the flow in the river and not the existence or operation of the project. A slight increase in pool elevation upstream of the dam may be observed due to the project. This increase is similar to that which would be caused by bridge piers and does not have a significant impact on the water surface or flows in the river.

3.4.2 Hinged Pool Operation

A hinged pool operation differs from a stair step operation in that the target pool elevation is maintained at a location upstream of the dam. As the flow increases, the water surface at the upstream end of the pool rises and the water surface near the upstream face of the dam lowers. At the present time, the only hinge pool now in operation on the Ohio River navigation system is at Emsworth L/D. A two foot reduction of the upper pool elevation is used to reduce the duration of high water conditions at Pittsburgh's Golden Triangle. The Olmsted Dam, now under construction, will be operated in accordance with a complex hinged pool plan with four target locations upstream of the project. The most significant target point is located fifty two miles upstream of the dam site.

3.5 MODELLING METHODS -- APPLICABILITY TO FEASIBILITY-LEVEL

3.5.1 Numerical Models

In order to provide additional information pertaining to the filling and emptying of the existing and modified lock chambers, a numerical model can be used. **T**ransient **F**low **SIM**ulation (TFSIM) is a one-dimensional computer model that was developed by Mr. Gerald Schohl of the Tennessee Valley Authority. The program permits a more detailed numerical analysis of the filling and emptying of a lock chamber compared with traditional methods commonly used by the Corps. TFSIM has the capability to evaluate flows and pressures at individual nodes anywhere within the lock culverts. In addition, it can model the variable water surface within the lock chamber. This information can be directly utilized when estimating hawser forces.

A revision to the TFSIM has been developed called LOCKSim. The more recent numerical analyses have utilized this updated program. The program is essentially the same as TFSIM but has been streamlined more for lock simulation. The results provided by the model are adequate for use as a screening level tool. Final design, however, should include a physical hydraulic model.

3.5.2 Physical Models

Physical Models

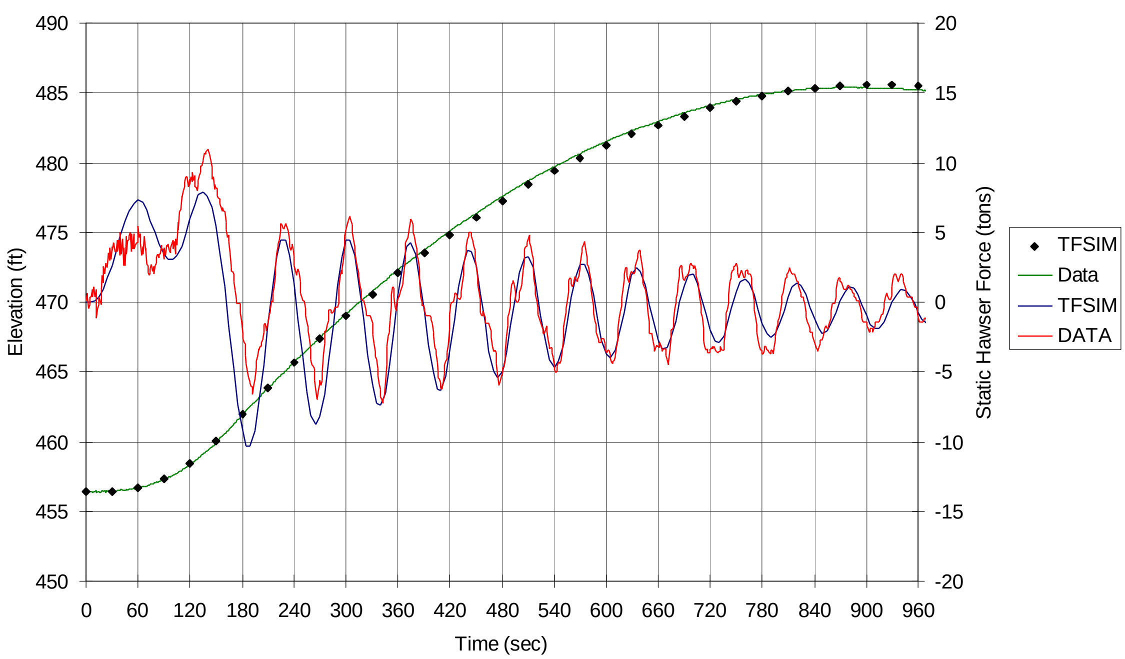
As part of the Innovation for Navigation Research Program at the Waterways Experiment Station (WES), hydraulic model studies will be performed on the extended 600-foot lock plans. Both unaugmented and augmented filling and emptying systems will be evaluated. Testing began this year on the unaugmented system but the data has not been compiled and made available for publication. A scope of services has been developed for WES to initiate testing for an augmented system, which will act as an Ohio River basin prototype for a number of potential projects. Testing is expected to being in FY00.

3.5.3 Prototype Data – Unaugmented E/F System

In July 1996, prototype data was collected at Meldahl L&D to evaluate the potential performance of the unaugmented lock extension plan. This condition was simulated in the prototype by filling the main chamber with the upstream laterals only. The test consisted of measurements of water surface elevation at various locations in the lock chamber. From these measurements, hawser forces were then estimated by multiplying the water surface slope by the weight of a 15 barge tow. The results were verified using the TFSIM numerical model. A filling curve for the prototype tests is provided in ***Figure 3.5.3A***.

Testing results indicate that the existing valve cycle time cannot be used to safely fill and empty an unaugmented auxiliary lock extension. The valve will have to be slowed to reduce water surface oscillations within the lock chamber. Model results indicate that fill times of sixteen minutes could be achieved with a five minute valve opening time. In addition, the downstream miter gate sill may be removed to alleviate any adverse impacts on the filling or emptying cycle. Under these operational conditions, hawser forces are expected to be less than five tons. The effect of miter gate sill removal will be further researched in order to determine whether or not removal is necessary.

FIGURE 3.5.3A MELDAHL PROTOTYPE - UNAUGMENTED F/E SYSTEM



SECTION 4

OTHER REGIONAL ENGINEERING AND GEOGRAPHICAL DATA

4.1 WEATHER CONDITIONS

Weather conditions are an important factor in the construction, maintenance, and tow traffic for any project on the Ohio River. These conditions include the general climate, temperature, and precipitation as well as adverse river conditions which includes wind-driven waves, storms, fog, and ice. Basic data has been gathered at a number of locations along the river since before the beginning of the 20th century. Numerous sources on the Internet system as well as the National Weather Service can be used to provide information. For the General Engineering portion of this study, only typical data and other information from each district are provided and discussed in the following paragraphs.

4.1.1 Climate

The Ohio River Basin is characterized by moderately extreme variations of temperature and precipitation. The climate is classified as humid continental with rainfall being fairly evenly distributed throughout the year. Because of varied topography and associated differences in local climates, generalized statements for humidity conditions cannot be made, with the exception that it is usually more intense in the early morning hours and tapers off shortly after noon.

The Ohio River Basin is a region of variable air mass activity that is subjected to polar, tropical, continental and maritime air mass movements. The passage of weather fronts associated with these air mass movements brings frequent and rapid changes in the weather. Prevailing winds come principally from the northwest, except in the summer months when the southwest direction predominates. Violent storms, including tornadoes, can occur in this area of the Ohio River basin and remnants of hurricanes can occur in the southeastern and eastern part of the basin.

4.1.2 Temperature and Precipitation

The average annual temperature in the Ohio River basin is in the mid to low 50 degrees Fahrenheit (ºF), with temperatures varying with location and elevation. Summer months are moderately warm and humid with annual average temperatures ranging between 70 and 80ºF. Winters are reasonably cold with annual average temperatures ranging between 20 and 40ºF.

The average annual precipitation for the Ohio River Basin is approximately 43 inches, varying from 52 inches in the southwest part of the basin to 56 inches in the southeast, and 36 inches along the northern divide. Snowfall averages 28 inches annually and constitutes only a minor portion of the total precipitation.

To provide a better comparison of the differences in temperature and precipitation through the length of the Ohio River, an internet source "http://mcc.sws.uiuc.edu" was selected because it covered most of the states in the basin and the data has a considerable length of record. This website entitled "Climate Summaries for the Midwest" covers locations in the states of Illinois, Indiana, Kentucky, Ohio, Pennsylvania and New York in the Ohio River Basin. Although numerous other stations are available, only three stations are presented in the General Engineering portion of the study. When choosing "Historical Climate Summaries" and the particular state and city, temperature and precipitation data are provided by month, by season, and annually for a number of different parameters which includes maximum, minimum and mean averages and date or number of days where appropriate. Tables 4.1.2-1 and 4.1.2-2 are presented for temperature and precipitation at Pittsburgh, PA representing the upper part of the river, Tables 4.1.2-3 and 4.1.2-4 at Ashland Dam 29, KY (just downstream from Huntington, WV) represents the middle reach of the river and Tables 4.1.2-5 and 4.1.2-6 at Louisville, KY represents the lower reach of the river. Some of the other stations will be utilized in the Site Engineering Appendices based on the project location.

Although the area exhibits a degree of homogeneity in climate, very hot and sub-zero temperatures often occur in the same year. Similarly, drought and flood events have been recorded in the same 12-month period.

TABLE 4.1.2-1
TEMPERATURE SUMMARY
PITTSBURGH, PA

Station: (366993) **PITTSBURGH**_WSCOM_2_AP   Missing Data: 0%

Averages: 1961-1990 Extremes: 1952-1996

	Averages Max	Min	Mean	Daily Extremes High	Date	Low	Date	Mean Extremes High	Yr	Low	Yr	#Day-Max => 90	#Day-Max <= 32	#Day-Min <= 32	#Day-Min <= 0
Jan.	33.7	18.5	26.1	69	01/1985	-22	19/1994	36.8	90	11.4	77	0	13	26	2.1
Feb.	36.9	20.3	28.6	69	15/1954	-12	11/1979	37.2	76	18.0	79	0	9.4	23	1.3
Mar.	49.0	29.8	39.4	82	30/1986	-1	09/1960	48.3	73	26.0	60	0	3.3	19	0.1
April	60.3	38.8	49.6	89	27/1990	14	08/1982	56.1	55	44.0	61	0	0.1	7.8	0
May	70.6	48.4	59.5	91	18/1962	26	02/1963	68.7	91	54.3	67	0.3	0	0.7	0
June	78.9	56.9	67.9	98	22/1988	34	11/1972	73.0	67	63.7	82	1.8	0	0	0
July	82.6	61.6	72.1	103	16/1988	42	09/1963	76.9	55	67.4	76	3.5	0	0	0
Aug.	80.8	60.2	70.5	100	17/1988	39	29/1982	77.8	95	65.3	76	2.3	0	0	0
Sep.	74.3	53.5	63.9	97	01/1953	31	19/1959	68.5	61	58.6	62	0.7	0	0	0
Oct.	62.5	42.3	52.4	87	06/1959	16	29/1965	59.5	71	45.9	76	0	0	3.8	0
Nov.	50.4	34.1	42.3	82	03/1961	-1	30/1958	47.7	94	33.1	76	0	1.4	14	0
Dec.	38.6	24.4	31.5	74	03/1982	-12	25/1983	39.9	82	19.2	89	0	9.4	24	0.7
Annual	60.0	40.8	50.4	103	07/16/88	-22	01/19/94	54.4	91	48.0	76	8.5	37	120	4.2
Winter	36.2	20.9	28.6	74	12/03/82	-22	01/19/94	35.4	53	20.5	77	0	32	73	4.1
Spring	59.9	39.0	49.5	91	05/18/62	-1	03/09/60	55.4	91	45.6	84	0.3	3.4	28	0.1
Summer	80.8	59.6	70.2	103	07/16/88	34	06/11/72	75.2	95	67.0	76	7.5	0	0	0
Fall	62.4	43.3	52.9	97	09/01/53	-1	11/30/58	56.2	71	46.3	76	0.7	1.4	18	0

TABLE 4.1.2-2
PRECIPITATION SUMMARY
PITTSBURGH, PA

Station: (366993) **PITTSBURGH**_WSCOM_2_AP   Missing Data: 0%

Averages: 1961-1990 Extremes: 1952-1996

	Total Precipitation Mean	High	Yr	Low	Yr	1-Day Max	Date	Snow Mean	High	Yr	#Days Precip =>.01	=>.50	=>1.
Jan.	2.54	6.25	78	0.77	81	1.23	2/1966	12.6	40.2	78	16.5	1.2	0.2
Feb.	2.39	5.98	56	0.51	69	2.29	23/1975	10.1	24.2	72	14.1	1.2	0.2
Mar.	3.41	6.10	67	1.14	69	1.82	9/1964	7.7	34.1	93	15.6	2.0	0.4
April	3.15	7.61	64	0.48	71	1.57	4/1957	1.7	8.1	87	13.6	1.9	0.4
May	3.59	6.56	89	1.21	65	2.31	24/1973	0.2	3.1	66	12.6	2.4	0.7
June	3.71	10.29	89	0.64	92	3.11	24/1996	0.0	0.0	53	11.6	2.5	0.8
July	3.75	8.71	92	1.62	89	2.96	11/1971	0.0	0.0	53	10.7	2.8	0.9
Aug.	3.21	7.86	87	0.78	57	3.06	5/1956	0.0	0.0	53	9.6	2.2	0.9
Sep.	2.97	6.00	90	0.28	85	2.09	4/1958	0.0	0.0	53	9.7	2.1	0.5
Oct.	2.36	8.20	54	0.16	63	3.56	15/1954	0.2	8.5	93	10.3	1.3	0.3
Nov.	2.85	11.05	85	0.90	76	1.80	16/1985	3.2	13.9	95	13.0	1.7	0.3
Dec.	2.93	8.51	90	0.40	55	2.76	30/1990	8.1	21.2	74	16.3	1.4	0.2
Annual	36.87	52.24	90	26.82	63	3.56	10/15/54	43.8	76.7	93	154.5	22.8	5.8
Winter	7.64	13.16	79	4.75	77	2.76	12/30/90	31.4	66.0	61	47.0	3.8	0.6
Spring	10.15	15.72	67	4.99	86	2.31	5/24/73	9.6	34.6	93	41.8	6.3	1.4
Summer	10.66	16.58	87	6.12	88	3.11	6/24/96	0.0	0.0	53	31.9	7.4	2.6
Fall	8.18	13.60	85	3.67	52	3.56	10/15/54	3.4	13.9	95	32.8	5.0	1.1

TABLE 4.1.2-3

TEMPERATURE SUMMARY

ASHLAND DAM 29, KY

Station: (150254) **ASHLAND_DAM_29** Missing Data: 2% '=prior to 1900 NCDC Averages

Averages: 1961-1990 Extremes: 1897-1996

	Averages			Daily Extremes				Mean Extremes				#Day-Max		#Day-Min	
	Max	Min	Mean	High	Date	Low	Date	High	Yr	Low	Yr	=> 90	<= 32	<= 32	<= 0
Jan.	41.0	18.1	29.5	80	26/1950	-25	19/1994	45.6	32	16.4	77	0	4.7	19	1.2
Feb.	44.9	20.1	32.5	79	28/1948	-23	10/1899	45.1	49	20.7	78	0	2.9	17	0.7
Mar.	56.7	29.5	43.1	92	26/1929	-8	15/1993	56.6	21	34.1	60	0	0.6	13	0
April	67.3	37.5	52.4	94	24/1925	16	20/1988	63.2	54	47.1	88	0.2	0	5.7	0
May	76.6	47.0	61.8	96	22/1941	22	02/1996	70.5	44	57.6	94	1.4	0	0.7	0
June	83.9	56.0	70.0	103	25/1930	30	10/1988	78.4	52	65.0	72	6.2	0	0	0
July	87.0	60.6	73.8	107	28/1930	34	01/1988	80.2	49	71.1	67	9.7	0	0	0
Aug.	85.8	59.2	72.5	105	04/1930	33	29/1986	79.1	47	67.7	92	7.8	0	0	0
Sep.	79.8	52.8	66.3	101	01/1932	27	23/1974	76.3	21	60.2	74	3.6	0	0.1	0
Oct.	69.0	40.2	54.6	93	07/1941	10	14/1988	64.2	47	43.6	88	0.2	0	3.5	0
Nov.	57.2	31.5	44.3	85	05/1948	2	30/1929	55.3	31	35.1	96	0	0.3	11	0
Dec.	45.7	23.0	34.4	82	04/1982	-18	23/1989	47.4	23	21.6	89	0	2.7	17	0.3
Annual	66.2	39.6	52.9	107	07/28/30	-25	01/19/94	61.1	20	49.4	88	29	11	87	2.3
Winter	43.9	20.4	32.1	82	12/04/82	-25	01/19/94	45.4	32	24.9	77	0	10	52	2.2
Spring	66.9	38.0	52.4	96	05/22/41	-8	03/15/93	60.5	21	48.0	88	1.6	0.6	20	0
Summer	85.6	58.6	72.1	107	07/28/30	30	06/10/88	78.2	52	68.8	92	24	0	0	0
Fall	68.7	41.5	55.1	101	09/01/32	2	11/30/29	63.8	31	48.1	88	3.8	0.3	15	0

TABLE 4.1.2-4

PRECIPITATION SUMMARY

ASHLAND DAM 29, KY

Station: (150254) **ASHLAND_DAM_29** Missing Data: 1% '=prior to 1900

Averages: 1961-1990 Extremes: 1897-1996

	Total Precipitation							Snow			#Days Precip		
	Mean	High	Yr	Low	Yr	1-Day Max		Mean	High	Yr	=>.01	=>.50	=>1.
Jan.	2.72	11.57	37	0.58	81	2.31	1/1945	3.6	13.5	96	11.6	2.4	0.6
Feb.	2.83	9.30	89	0.29	41	2.40	3/1939	1.4	13.0	34	10.5	2.0	0.4
Mar.	3.59	8.41	94	1.27	69	2.63	12/1939	0.9	24.0	93	12.6	2.6	0.7
April	3.60	7.62	39	1.09	86	2.67	6/1936	0.0	3.0	44	11.6	2.3	0.6
May	4.26	9.37	96	0.83	64	3.21	14/1955	0.0	0.0	32	12.2	2.7	0.8
June	3.83	8.49	62	0.60	66	4.09	12/1962	0.0	0.0	32	10.1	2.5	0.8
July	4.87	11.03	61	1.07	44	5.61	20/1973	0.0	0.0	32	10.4	3.0	1.1
Aug.	3.96	8.36	79	0.51	32	3.97	4/1933	0.0	0.0	32	9.3	2.3	0.9
Sep.	2.81	8.53	50	0.47	85	3.72	17/1995	0.0	0.0	32	7.6	1.9	0.7
Oct.	2.94	6.61	83	0.13	63	2.84	22/1929	0.0	0.0	32	7.9	1.6	0.6
Nov.	3.37	8.17	21	0.52	76	3.10	17/1927	0.2	14.6	50	10.9	1.9	0.6
Dec.	3.44	9.22	90	0.40	65	3.00	29/1993	1.5	14.2	35	11.1	2.0	0.5
Annual	42.22	61.41	89	23.28	30	5.61	7/20/73	6.3	34.0	93	124.0	26.9	8.3
Winter	8.99	18.46	37	4.34	77	3.00	12/29/93	7.8	22.9	94	33.6	6.4	1.6
Spring	11.45	18.55	67	5.17	41	3.21	5/14/55	0.9	24.0	93	36.7	7.7	2.1
Summer	12.66	21.71	79	3.98	57	5.61	7/20/73	0.0	0.0	32	30.2	7.9	2.8
Fall	9.12	15.91	50	2.76	30	3.72	9/17/95	0.2	14.6	50	27.3	5.6	2.0

TABLE 4.1.2-5

TEMPERATURE SUMMARY

LOUISVILLE, KY

Station: (154954) **LOUISVILLE**_WSO_AIRPORT   Missing Data: 0% NCDC Averages

Averages: 1961-1990 Extremes: 1948-1996

	Averages			Daily Extremes				Mean Extremes				#Day-Max		#Day-Min	
												=>	<=	<=	<=
	Max	Min	Mean	High---Date		Low---Date		High-Yr		Low-Yr		90	32	32	0
Jan.	40.3	23.2	31.7	77	25/1950	-22	19/1994	44.6	50	18.6	77	0	7.7	23	1.1
Feb.	44.8	26.5	35.7	77	13/1962	-19	02/1951	45.4	76	23.8	78	0	4.3	19	0.3
Mar.	56.3	36.2	46.3	86	31/1981	-1	06/1960	53.7	73	32.5	60	0	0.7	13	0
April	67.3	45.4	56.3	91	23/1960	22	07/1982	62.4	81	49.5	61	0.1	0	2.1	0
May	76.0	54.7	65.3	95	04/1959	31	01/1963	73.1	91	59.0	61	1.0	0	0.1	0
June	83.5	62.9	73.2	102	29/1952	42	01/1966	80.6	52	68.7	74	7.2	0	0	0
July	87.0	67.3	77.2	105	14/1954	50	27/1962	82.0	93	74.2	60	13	0	0	0
Aug.	85.7	65.8	75.8	101	31/1953	46	29/1986	82.3	95	72.2	67	11	0	0	0
Sep.	80.3	58.7	69.5	104	05/1954	33	30/1949	74.2	54	63.2	74	3.8	0	0	0
Oct.	69.2	45.8	57.6	92	02/1953	23	22/1952	64.4	71	51.9	52	0.2	0	1.6	0
Nov.	56.8	37.3	47.1	84	17/1958	-1	25/1950	53.7	85	39.4	51	0	0.5	10	0
Dec.	45.1	28.6	36.9	76	03/1982	-15	22/1989	45.9	84	25.3	89	0	4.0	20	0.3
Annual	66.0	46.0	56.1	105	07/14/54	-22	01/19/94	59.8	91	54.5	60	36	17	89	1.7
Winter	43.4	26.1	34.8	77	01/25/50	-22	01/19/94	41.8	50	27.2	78	0	16	62	1.6
Spring	66.5	45.4	56.0	95	05/04/59	-1	03/06/60	61.1	77	52.1	61	1.1	0.7	15	0
Summer	85.4	65.3	75.4	105	07/14/54	42	06/01/66	79.6	52	73.2	74	31	0	0	0
Fall	68.8	47.3	58.1	104	09/05/54	-1	11/25/50	61.9	73	52.9	76	4.0	0.5	12	0

TABLE 4.1.2-6

PRECIPITATION SUMMARY

LOUISVILLE, KY

Station: (154954) **LOUISVILLE**_WSO_AIRPORT   Missing Data: 0%

Averages: 1961-1990 Extremes: 1948-1996

	Total Precipitation							Snow			#Days Precip		
	Mean	High--Yr		Low--Yr		1-Day Max		Mean	High– Yr		=>.01	=>.50	=>1.
Jan.	2.86	11.38	50	0.45	81	3.00	19/1988	5.9	28.4	78	11.4	2.2	0.7
Feb.	3.30	9.02	89	0.76	78	3.66	15/1990	5.0	15.9	93	10.6	2.2	0.8
Mar.	4.66	14.91	64	1.03	66	6.97	9/1964	3.1	22.9	60	13.0	2.9	0.9
April	4.23	11.10	70	0.76	76	4.08	1/1970	0.2	1.6	73	11.7	2.6	0.9
May	4.62	11.57	90	1.37	77	4.60	7/1961	0.0	0.0	49	11.8	3.3	1.2
June	3.46	10.11	60	0.49	84	5.12	23/1960	0.0	0.0	48	9.9	2.4	0.8
July	4.51	10.05	79	0.99	83	5.09	21/1973	0.0	0.0	48	10.4	2.8	1.0
Aug.	3.54	8.79	74	0.23	53	3.12	8/1992	0.0	0.0	48	8.3	2.3	0.8
Sep.	3.16	10.49	79	0.27	53	4.30	21/1979	0.0	0.0	48	8.1	2.0	0.7
Oct.	2.71	6.47	83	0.39	87	2.64	22/1983	0.0	2.4	93	7.6	1.7	0.6
Nov.	3.70	9.12	57	0.72	76	3.58	5/1948	1.0	13.2	66	10.4	2.9	0.9
Dec.	3.64	8.86	90	0.65	76	2.77	3/1978	2.2	9.3	61	11.5	2.6	0.9
Annual	44.39	59.80	79	30.38	53	6.97	3/ 9/64	17.4	43.1	78	124.7	30.0	10.1
Winter	9.80	21.94	50	4.43	77	3.66	2/15/90	13.2	35.9	78	33.9	7.1	2.4
Spring	13.51	21.44	61	6.16	54	6.97	3/ 9/64	3.3	22.9	60	36.5	8.8	3.0
Summer	11.51	17.00	77	5.93	94	5.12	6/23/60	0.0	0.0	48	28.6	7.6	2.6
Fall	9.57	18.61	79	2.97	53	4.30	9/21/79	1.1	13.2	66	26.1	6.6	2.2

4.1.3 Adverse Conditions

Among the adverse conditions that can result in navigation stalls on the Ohio River are wind-driven waves, storms, fog, and ice. Navigation stalls are delays that figure into the economic aspects of the benefits of additional lock capacity. However, the records at the respective locks do not fully account for these adverse conditions because the information is more at the discretion of the lockmaster.

4.1.3.1 Wind-Driven Waves

Prediction of wind generated waves and assessing their interaction with the riverbanks and lock and dam structures are of considerable importance from the standpoint of external forces, freeboard, and slope propagation. Wind waves on the Ohio River probably have their greatest effect on tows making their approach into lock chambers.

Actual records of wind velocities are not available immediately along the Ohio River. However, records at Pittsburgh, the nearest first-order National Weather Service station with wind velocity data, are applicable to the Ohio River. In actuality, overwater windspeeds may be increased or decreased due to instabilities arising from differences in air-water temperatures. The Pittsburgh velocity station is located on a mountain ridge 450 feet higher in elevation and 1 mile southwest of Dashields Locks and Dam. The records indicate that high winds have a predominantly western component. Analytically, the maximum velocity determined for one minute, in any direction, was in excess of 90 miles per hour; the maximum for one hour was 56 miles per hour. High wind velocities may occur simultaneously with maximum river stages. During the passage of a cold front at the time of the flood crest on 5 March 1963, gusts from the southwest of about 63 miles per hour with an hourly average of 40 miles per hour were recorded at the Pittsburgh station.

Actual records of wave heights are not available for the Ohio River. In the Pittsburgh District, the waves are theoretically largest in Pike Island pool where there is maximum generating area. Design wave heights of 2.8 feet were computed using the theoretical maximum wind speeds and the actual March 1963 wind speeds. Wave heights of 2.1-2.6 feet were computed for other reaches of the river.

In the Huntington District, prevailing winds are from westerly directions, averaging 5 to 7 MPH during the summer and winter months, respectively. Damaging winds occur most often during spring and summer months and are associated with major thunderstorms. There are several types of storm activity that can be expected to occur in the Ohio River Basin. The most frequent is a result of the passage of warm, moist air from the south or southwest coming into contact with the cooler, often drier, air from the north or northwest.

4.1.3.2 Storms

Flood producing storms, generally occurring in late winter through early spring months, are of two types. The first of these is characterized by long duration with relatively low intensity and of a wide extent. The opposing action of two large stationary anticyclones, or "highs", one located off the Atlantic Coast and the other entrenched over the upper portions of the Mississippi and Missouri Basins, creates this type of storm. A stationary front lying northeast to southwest across the Ohio River Basin is produced. Along this front, a succession of "moist waves" may move northeastward, resulting in bursts of copious warm rains for prolonged periods. The condition continues to exist until there is a displacement of one or both of anticyclones. A tremendous amount of water falls during this type of storm.

Another type of storm causes moderate to fairly heavy and sometimes intense precipitation for a short duration and over broad but smaller area. One or more closely related cyclones, or "lows", are responsible. The impact of this type of storm on the area is compounded by the fact that it most frequently occurs between December and April, when soils are generally saturated. The storms occasionally occur during the summer months which permits the soil to absorb a larger quantity of rainfall, therefore, resulting in lower runoff.

A study of past flood producing storms indicates that the general northeast-southwest alignment would continue. However, the storm center with heaviest rains could be transposed to almost any point in the Ohio River Basin, still distribution of rainfall would be affected by topographic features. Moderate rainfalls can occur on the perimeter of each storm. Storms may result in up to 15 inches of rainfall during a two- to five-day storm period. Areas as large as 20,000 square miles may experience 24-hour rainfalls in excess of six inches. The Ohio River Basin may experience several of these two- to five-day storms in succession, separated by only three or four days of clear weather. Thunderstorms often yield intense local rainfall that may cause flash flooding on small streams. The Ohio River Basin averages 30 to 50 days of thunderstorms each year, only a few severe.

4.1.3.3 Fog

Morning fog is frequent along the Ohio River, often persisting until late morning. Based on 62 years of records at Pittsburgh from 1908-1969, fog occurs an average of 24 days per year. Montgomery Locks and Dam had an average of 75 days per year of fog based on 4 years of records. The fog is dense enough about half of the time to adversely affect navigation visibility and extend lockage times. If fog conditions are severe, tows will tie off on mooring cells or on approach walls until the fog recedes.

In the Huntington District, heavy fog occurs most frequently during spring, summer and fall, with some averaging at least 50 days of heavy fog each year. These areas, particularly in the more industrial reaches, are especially susceptible to atmospheric stagnation.

4.1.3.4 Ice

Ice on the Ohio River varies from the more northern mountainous part of drainage basin upstream in the Pittsburgh District reach of the stream to a lesser degree in the Louisville reach.

Investigations of records indicate that ice can form on the pools when temperatures drop near 0° F. All of the District's pools have occasionally remained frozen several inches thick during extended cold spells. Massive ice gorges originating in the upper Allegheny River sometimes pass through the pools. The maximum ice thickness recorded on the Ohio River for the period of 1961-1997 is 12 inches. The winters of 1976-77 and 1977-78 are two of the worst winters on record for the Ohio River. Montgomery L/D recorded 37 days of ice for the 1976-77 winter with an average ice thickness of 5.1 inches and 38 days of ice and an average thickness of 4.1 inches for the 1977-78 winter.

Investigations of ice conditions throughout the Pittsburgh District indicate that the primary factor in moving ice out of navigation pools is an appreciable increase in river flow. This may produce a higher river stage and a slope in the pool level. The rise in stage cracks and dislodges the ice from the riverbanks and destroys the cohesion of the ice sheet. The increased slope of the stream profile accompanied by an increase in velocity then serves to transport the ice downstream.

Traffic on the Ohio River is sufficiently heavy that navigation channels normally remain open even after the river freezes over. The greatest interference to navigation, however, is caused not by ice conditions in the pools, but the accumulation of floating broken ice in the upper lock approaches and lock chambers. The fragmented ice can become wedged between the miter gates and the recess walls causing the gates to be restricted from retracting completely. Damage to the gates and machinery is possible.

In the Pittsburgh District, ice accumulation in the upper approaches is removed by several methods. All of the locks conduct ice lockages. The lower three locks, New Cumberland L/D, Pike Island L/D and Hannibal L/D place bulkheads in the 600 feet long chamber to use as a spillway to pass ice. Emsworth L/D and Montgomery L/D do not have this capability but have fixed crest weirs next to the locks which help pass ice. If flow conditions permit, ice is also diverted through dam gates according to the gate operating schedule. Dashields L/D is a fixed crest dam.

Air bubbler systems have been installed on all of the Pittsburgh District's six projects for both the large and small chambers, upper and lower gates. The bubbler systems consist of an air bubbler screen upstream of the miter gates to prevent ice from entering the lock and flushers located in the miter gate recesses to clear the recess area so the gates can completely retract. The bubbler systems have been very effective in reducing winter lockage times. It has also become standard operating procedure to use the bubblers during all lockages to remove debris.

SECTION 5

COMPARATIVE INSPECTION OF MAIN STEM LOCKS (1996)

One of the first tasks of the Engineering Team's Without-Project group was the visual inspection of all Ohio River Mainstem projects by a single team or "jury" of structural engineers. This inspection team was lead by Mr. Terry Shilley of Pittsburgh District, and the entire 20-lock evaluation was documented in a report entitled ***Ohio River Mainstem Systems Study, Field Inspection Report (1997).***

This following are excerpts from the 20-lock report, including the report's "Executive Summary" and the project data for J.T. Myers and Greenup Locks (two projects only).

5.1 EXECUTIVE SUMMARY

An integral part of the Ohio River Mainstem Study is the visual assessment of the current physical condition of the major components of the existing projects as a beginning point for predicting future performance. The initial effort in this assessment involved the on-site inspection of all Ohio River navigation projects. The inspections were primarily visual, supplemented by evaluation of recent Periodic Inspection reports, maintenance records and discussions with lockmasters and lock maintenance leaders. This report reflects only the evaluation of the physical condition of the components at the time of the inspection and is intended to serve as a broad overview of the project condition. It was not an in-depth inspection and was limited by access to all areas of the components. Engineering analyses, to aid in determining the adequacy of the components to continue to perform as intended, are included in another volume of the report entitled "Reliability of Lock and Dam Components".

This document is a compilation of the field inspection reports for each Ohio River project and provides a narrative description and project numerical rating, based on the REMR rating system which was developed by the Waterways Experiment Station, Vicksburg, Mississippi, of each of the major components of the eighteen lock and dam projects located along the Ohio River mainstem. Input from project personnel regarding component operational and maintenance history was vital in helping assign a rating to the components. The projects visited were Emsworth, Dashields, Montgomery, New Cumberland, Pike Island and Hannibal in the Pittsburgh District; Willow Island, Belleville, Racine, Robert C. Byrd, Greenup and Meldahl in the

Huntington District; Markland, McAlpine, Cannelton, Newburgh, Myers and Smithland in the Louisville District. The sites below Smithland Locks and Dams (Locks and Dam 52 and 53, and the Olmsted construction site) were visited for information only, and are not included in this report. The Olmsted project was still under construction (lock cofferdam contractor working at the site) and Locks and Dams 52 and 53 are planned to be removed from service once Olmsted becomes operational.

The Field Inspection Team consisted of a "core group" of engineers supplemented by additional personnel from each District. This "core group" provided consistency during the field inspections, during the on-site interviews with project lockmasters and maintenance leaders and while assigning the numerical ratings. This team was made up of civil and structural engineers from each of the three district offices, as follows: Pittsburgh District: Terry D. Shilley, Civil Engineer; Huntington District: Rob Taylor, Structural Engineer, Jason Merritt, Structural Engineer, Scott Wheeler, Structural Engineer; Louisville District: David Schaaf, Structural Engineer. The Huntington District inspection team changed personnel during the summer of 1996, due to Rob Taylor taking a position in the ORD offices in Cincinnati, Ohio. At that time, Mr. Taylor was replaced by Mr. Merritt and Mr. Wheeler. The change was made while assessing projects already visited and did not alter the "common" ratings for the projects.

A list of major components was developed by the team members prior to the inspection of the first project. This list was created based on the significance of the component to the overall operation of the project, and is generally commensurate with the list of items on which reliability analyses are being performed although the reliability screening process was not yet complete at the time of the inspections. A lock component was considered significant if its unsatisfactory performance could cause a chamber closure of 8 hours or more. For the dam, since component unsatisfactory performance does not necessarily affect lock closure, the list was derived by evaluating the economic and operational consequences of failure of the various dam components.

The major components inspected for the locks are: Wall Monoliths (land, middle and river wall monoliths), Guide and Guard Walls (upper and lower guide and guard walls), Lock Gates (vertically and horizontally framed miter gates), Culvert Valves (butterfly and reverse tainter valves). The components inspected for the dams are as follows: Concrete Piers, Dam Gates (vertical lift, sidney, tainter, and roller gates), Emergency Bulkheads, Dam Service Bridge, Fixed Weir, Cutoff Wall, and Geotechnical features (streambanks, erosion problems).

Each of the eighteen project reports included herein is formatted similarly, to narratively describe the conditions and numerically rate major components of the projects.

5.2 J.T. MYERS LOCKS AND DAM

Terry Shilley (ORP), Carl Knoth (ORP), Rob Taylor (ORH), and David Schaaf (ORL) visited the J.T. Myers L&D site (then called Uniontown L&D) on 20-21 June 1995. The inspection was held over both days. Project personnel interviews were conducted on 21 June 1995.

Overall, the project was in good condition. The inspection consisted of a general walk-thru of the entire project. Because the main chamber was dewatered for maintenance, an inspection of the main chamber culverts was possible. No problems were encountered that would indicate immediate concern to safety of the structure. However, considerable problems were encountered that will require attention in the future. Among these are cracking/spalling of the crane bridge girder seats and emergency bulkhead dogging platforms. A contractor made repairs to these areas in 1991, but it has been a constant problem over the life of the structure due to an initial design error. It was determined by an engineering analysis several years ago that an insufficient amount of steel reinforcement was provided in the girder and bulkhead bearing areas.

Also, misalignment of the end monoliths for both the upper and lower guard walls occurred shortly after construction. Subsequent monitoring of these monoliths has shown that the movement has stabilized. Significant spalling of the upper guard wall has occurred over the years and poses potential hang-up spots for barges during their approach into the chamber. Refer to the general inspection result sheets and photos for further information.

Other problem areas were addressed by project personnel during an interview. Among the problems are the poor lighting system and lack of public address system. The lighting system is obsolete and there is no PA system. The tainter gate dam indicators are obsolete and no longer work. The site would benefit with a better handrail system. See the project personnel interview sheet for further details.

Additionally, the site is located in a potentially high seismic area, near both the Wabash and New Madrid Fault Lines. It is unsure whether seismic analyses have been conducted for the structures at the site. This may be a considerable potential for damage/repairs over the next 50 years, the time frame for which the Ohio River Mainstem Study is being developed.

5.2.1 Project Personnel Interview

Personnel Interviewed: Gary Dawes (Lockmaster)
Date: June 21, 1995

Several issues were discussed with the lockmaster, Gary Dawes, about the condition of J.T. Myers Locks and Dam. Mr. Dawes started working at J.T. Myers Lock and Dam in 1974 as a maintenance mechanic. He has served as lockmaster since 1988. The following is a brief overview of important thoughts presented by Mr. Dawes during the interview.

- Additional 1200-ft Lock. The biggest need at the site is an additional 1 200-ft lock according to Mr. Dawes. This could be accomplished by adding to the 600-ft chamber or providing a new lock. Studies are presently under way. Severe capacity problems are encountered at J.T. Myers when the 1200-ft chamber is dewatered for maintenance and inspection purposes. It is considered the bottleneck on the Ohio River.
- Lighting System/PA System. The lighting system is extremely poor. The system is obsolete and repairs are make shift since replacement parts can not always be found. Additionally, there is an urgent need for a public address system on-site because it is extremely difficult to reach personnel in the event of an emergency.

- Handrail System. The lockmaster would also like to see a revamped or new handrail system installed. Better designs are now available which would make operations extremely more useful and efficient. Speed-rail systems are readily available.
- Tainter Gate Indicators. The dam tainter gate indicators are no longer functional and need to be replaced. The system is obsolete.
- Zebra Mussels. Zebra mussels on-site and could pose a considerable problem in the future.
- Intake Screens. The intake screens will need to be replaced in the future.
- Concrete Sealing. The contractor repairs to the cracking and spalling at the bulkhead dogging platform and crane bridge girder seats were holding well at the time of the inspection. The repairs were made in 1991. An engineering evaluation determined that the bridge seats were under reinforced at the girder bearing locations. The contractor that made the repairs stated that considerable life could be added to the concrete on-site if a proper crack sealing program was initiated.
- River Channel Erosion. River channel erosion just downstream of the dam is known to have occurred. Previous soundings revealed erosion was the worst between gate bays #6 through # 10. See the inspection results for further details.
- Riprap Protection. Additional riprap protection at the upper end is required after high water because tows hit the upstream bank during their approach.
- Miter Gates. The original miter gates are being used in both chambers. Considerable repairs/replacement will be required in the future as the gates continue to age.
- The lockmaster stated that there were no major ice or drift problems at the site. The items listed above are considered problem areas in the future.

5.2.2 General Inspection Results

Site: J.T. Myers Lock and Dam
Location: Mile 846 below Pittsburgh, PA, 3 I/2 miles downstream from J.T. Myers, KY
Date of Inspection: June 20-21, 1995
Inspectors: ORP: Terry Shilley and Carl Knoth ORH: Rob Taylor ORL: David Schaaf

5.2.2.1 Rating Guidelines for All Components

VALUE	CONDITION	DESCRIPTION
85-100	Excellent	No noticeable defects. Aging/wear may be visible.
70-84	Very Good	Only minor deterioration or defects noticeable.
55-69	Good	Deterioration noted but function not significantly affected.
40-54	Fair	Moderate deterioration; function slightly affected.
25-39	Poor	Serious deterioration; function is inadequate
10-24	Very Poor	Extensive deterioration; barely functional.
1-9	Failed	No longer functional, needs major repair or replacement.

5.2.2.2 Lock Inspection

Lock Information: The two adjacent parallel lock chambers are located along the Indiana shore. The main lock, riverside, has clear dimensions of 110 x 1200 feet and the auxiliary lock has clear dimensions of 110 x 600 feet. Two sets of hydraulically operated steel miter gates are provided for each lock. The construction of the locks and guide/guard walls began in 1965 with completion in 1972. The average age of the lock and guide/guard wall concrete is 27 years.

5.2.2.3 Wall Monoliths

Landside Chamber Wall Monoliths -- Wall Type: Concrete Gravity on Rock -- Rating: 80

- Alignment: Looked good, no problems noted during this walk-thru or from the last periodic inspection, which occurred during June 1991.
- Cracking: Typical surface cracking noted. No other serious cracking noted. No problems from the last periodic inspection.
- Spalls: No major spalling noted.
- Other: Typical rusted wall armor. Surface rusting of floating mooring bit contact points. Future Considerations/Notes: The landside chamber monoliths appeared to be in good condition. No major problems have been noted during previous periodic inspections. Continued corrosion of the wall armor and floating mooring bit-associated metals will cause need for repair/replacement over the next 50 years. Replacement of intake screens periodically will be required in the future. It may be beneficial to adapt the design to have removable intake screens.
- Funding Considerations: All items discussed for the landside wall would fall under regular O & M funding. One alternative to this may be if a new intake screen design were to be utilized, the new design may be incorporated as part of a major rehab.

Middle Wall Chamber Monoliths -- Wall Type: Concrete Gravity on Rock -- Rating: 70

- Alignment: Alignment was good. No problems noted from previous periodic inspections.
- Cracking: Crack and efflorescence noted at the landside, downstream miter guide recess, see photo # 1. This crack has been noted previously and is not considered a problem.
- Spalls: Spall noted on middle wall river side chamber face near 200' marker. Probably due to barge action during high water and noted during the last periodic inspection, see photo #2.
- Other: Leakage was noted at five monolith joints in the culvert and riverside faces of the middle wall, see photo #3. During the walk-thru of the middle wall culvert for the main chamber, spalling and slight vertical offsets were noted at two monolith joints. One appears to be a patch or a repair that did not hold during construction, while the other looks like a spall or local buckling action, see photo #4. Both were noted during the past periodic inspection, and are not considered problems because surface movement was not noted at these areas. These areas should be checked closely in future periodic inspections.
- Future Considerations/Notes: The leakage at the monolith joints is not considered serious, but should be monitored during future inspections. The monoliths associated with the leaking

joints should be visually monitored to ensure movement of the monolith is not occurring. Same notes as listed for the landside walls applies to the middle walls.

- Funding Considerations: All funding requirements for repairs would fall under regular O & M.

River Wall Chamber Monoliths--Wall Type: Concrete Gravity on Rock--Rating: 70

- Alignment: The river wall alignment looked good. No problems were noted.
- Cracking: Considerable surface cracking was noted at some of the upstream monoliths, see photo #5. Heavy cracking in the upstream culvert valve bulkhead was noted. This has been a problem area noted in previous periodic inspections. The propagation of the crack vertically down the monolith has caused concern regarding it structural stability, see photo #6 of the vertical cracking.
- Spalls: No problems were noted.
- Other: Local warping of top cover plate at 150' downstream of the downstream miter gates. This is not considered a serious problem.
- Future Considerations/Notes: Continued monitoring of the cracking at the upstream culvert bulkhead should continue. The monolith is to be structurally analyzed by the District's Engineering Division to account for the crack in the monolith. This is in response to the comments from the previous periodic inspection.
- Funding Considerations: Depending upon the results of the structural analysis, the repairs would probably be covered under regular O & M funding. If large scale repairs are necessary, major maintenance funds would be required or the repairs would be made at the time of a major rehab.

5.2.2.4 Guide/Guard Walls

Upper Guide (Landside) Wall -- Wall Type: Concrete Gravity on Rock --Rating: 85

- Alignment: No problems noted.
- Cracking: No problems noted.
- Spalls: No problems noted.
- Other: Erosion control around the upstream end of the wall would benefit from additional stone protection.
- Future Considerations/Notes: The upper guide wall looked to be in excellent condition. The only problem area noted was the potential for erosion damage around the last monolith. Presently, the erosion control is adequate, however, repeated flooding over time could damage the minimal control that now exists. This is typical for the downstream guidewall as well, see photo #7.
- Funding Considerations: All repair items would be covered under regular O & M funding, unless the additional riprap was included as part of a major rehab at J.T. Myers.

Upper Guard (Riverside) Wall -- Wall Type: Concrete Gravity on Concrete -- Rating: 70 (Filled Cells)

- Alignment: The monolith joint R96-R97 had significant amount of differential horizontal and vertical movement, see photo #8. This occurred just after construction. The movement has been monitored over the years and has not varied significantly since its initial movement.
- Cracking: Horizontal crack at 265' upstream of upper miter gates. This crack proceeds vertically below upper pool.
- Spalls: Spall area noted at 325' mark probably due to barge action, see photo #9.
- Other: No other defects noted.
- Future Considerations/Notes: The misalignment has been monitored over the years and has not presented a problem. The horizontal crack noted earlier should be monitored in the future. The spall area provides a potential hang-up for barges. Repairs should be made if warranted.
- Funding Considerations: Regular O & M funding would be used for all items. However, as part of a major rehab project at J.T. Myers, repairs would be made to R96-R97.

Lower Guide (Landside) Wall -- Wall Type: Concrete Gravity on Rock--Rating: 85

- Alignment: No problems noted.
- Cracking: No problems noted.
- Spalls: No problems noted.
- Other: Additional riprap around the downstream end may be beneficial.
- Future Considerations/Notes: Presently, the erosion control is adequate. However, repeated flooding over time could damage the minimal control that now exists. Overall, the lower guide wall appears to be in excellent condition.
- Funding Considerations: Same funding notes apply as listed for the upper guide wall.

Lower Guard (Riverside) Wall -- Wall Type: Concrete Gravity on Rock -- Rating: 75 (Granular-filled Cells)

- Alignment: Some time after construction, differential movement occurred at monolith joint Rl-R2, see photo #10. Alignment pins were installed and measurements have since indicated minimal movement since the initial occurrence.
- Cracking: No significant cracking noted.
- Spalls: No significant spalling noted.
- Other: No other defects noted.
- Future Considerations/Notes: The differential movement does not appear to cause a problem.
- Funding Considerations: Regular O & M funding will be used for any repairs to this wall. However, as part of a major rehab project at J.T. Myers, repairs would be made to R1-R2.

5.2.2.5 Lock Gates

Auxiliary (Landside) Chamber Lock Gates -- Gate Type: Horizontally Framed -- Rating: 80 (Miter Gates (Steel))

- Appearance: Overall, gates looked good. Slight wear and tear was noticeable. Surface corrosion noted on the quoin and miter blocks, which were installed in 1990. Only the part of the miter gate above the water line could be inspected for this chamber. Paint appeared to be in excellent condition above the water line.
- Anchorage: light spalling noted at miter gate anchorages, not considered serious.
- Leakage: Good side seals noted at upper miter gate. Leakage noted at upper miter block seal, see photo # 11. Leakage noted at quoin block on lower miter gate. Lower miter gate had good miter block seal. None of the above considered serious.
- Machinery: No problems noted.
- Sill: Under water, not inspected. However, no problems noted in previous inspections.
- Other: No noise or vibration noted during operation.
- Future Considerations/Notes: The gates appeared to be in good condition. However, these are the original gates that are approximately 27 years old. Gate replacement will be required over the next 50 years. The option of a gate change-out system is presently being developed by the District. If this scenario takes place, all gates within the District would be modified so all are interchangeable. Spare gates would be available for periodic replacement under the gate changeout scenario. Presently, replacement of the pintles, gudgeon pins, and other assorted items takes place about every 10 years, with inspection dewaterings every 5 years.
- Funding Considerations: Under the present scheduling, major maintenance funds would be used for the l 0 year maintenance schedule described above. Inspection dewaterings and painting would fall under regular O/ M funding. Once on-line, the gate changeout program would probably fall under regular O/M funding. However, the construction of spare gates and modifications to the existing gates may fall under a separate funding category.

Main (Riverside) Chamber Lock Gates -- Gate Type: Horizontally Framed -- Rating: 80 (Miter Gates (Steel))

- Appearance: Overall, the gates looked good. General surface corrosion noted on both sides of gate which are typically under water, see photo # 12. Paint system is in good condition above the water line and in fair condition below the water line.
- Anchorage: Spalling was noted on the riverside at the anchorage. Movements of anchorage mechanism in the middle wall during operation of the gate caused enough concern that repairs to the anchorage at the upper and lower middle wall were undertaken during the June 1995 dewatering. A stiffer connection was made to the embedded anchorage at these locations. The remaining anchorages are to be repaired in the future.
- Leakage: Gates were not in operation during the chamber dewatering.
- Machinery: The machinery was inspected during the dewatering and minor repairs were made where necessary by maintenance personnel. No significant problems noted.
- Sill: Miter gates sills and emergency bulkhead sills looked good, see photo #13. No noticeable defects were noted.
- Other: No other problems noted.

- Future Considerations/Notes: The gates appeared to be in good condition. Surface corrosion noted below the water line is not serious at this time. Sweeper plates were added at the base of each gate in the land chamber to clear debris and make a better seal at the miter gate sill. The a gates were closely inspected during this recent dewatering by maintenance personnel and found to be in satisfactory condition. The same notes pertaining to gate repairs and replacement from the auxiliary chamber miter gates apply to the main chamber gates.
- Funding Considerations: The same notes apply as stated for the auxiliary chamber miter gates.

5.2.2.6 Culvert Valves

Auxiliary (Landside) Chamber Culvert Valves -- Type: Reverse Tainter Gates -- Rating: 75

- Appearance: Based upon limited viewing capability, the overall appearance looked good. Surface corrosion was noted. No problems noted from previous periodic inspections or mentioned by lock personnel.
- Machinery: No problems noted during operation.
- Other: No problems noted.
- Future Considerations/Notes: No problems were noted during the last periodic inspection. A good view of the culvert valves for the auxiliary chamber could not be obtained because of the grating which covers the valve. During the 1990 dewatering, all nuts and grease lines were repaired. Magnesium anodes were welded to the side guides. The culvert valves are also original and will need to be replaced over the next 50 years as part of a major rehab.
- Funding Considerations: Repairs to the culvert valves are typically covered under regular O/M funding. Major repairs would be covered by major maintenance funds. Replacement of the culvert valves would occur during a major rehab at J.T. Myers.

Main (Riverside) Chamber Culvert Valves -- Type: Reverse Tainter Gates -- Rating: 75

- Appearance: A better view was obtained for these culvert valves because of the dewatering.
- Considerable surface corrosion was noted at some locations, see photo # 14. The seals, which were reworked during the 1989 dewatering, were in excellent condition.
- Machinery: No problems noted during previous periodic inspections.
- Bulkheads: The culvert valve bulkheads appeared to be in good condition. All welds were recently tested and were determined to be adequate. The paint on the culvert bulkheads was in satisfactory condition, see photo #15.
- Other: No other problems noted.
- Future Considerations/Notes: The valves appear to be in good condition. However, a protective painting may be required in the near future. Surface corrosion was noted at most locations of the culvert valve. Surface corrosion at the trunnion beam caused some flaking and minor loss of material properties. This is not considered critical at this time, however, it will present a problem in the future if the valves are not protected or parts replaced as necessary.

- Funding Considerations: Surface preparation, painting, and individual part replacement would be covered under normal O/M funding. The same notes apply to the replacement/major repair of the main chamber culvert valves as was listed for the auxiliary chamber culvert valves.

5.2.2.7 Miscellaneous Items

- Control Structures: No significant problems noted. Electrical/Lighting: According to lock personnel, the lighting system is obsolete and inadequate. Replacement parts can not be found. Also, there is a critical need for a public address system on-site. It is very difficult to reach individuals at different parts of the site in the event of an emergency.
- Maintenance Equip: No problems noted.
- Safety: According to the lockmaster, a better, updated removable handrail system would be a major benefit. There are systems presently which are much more user-friendly and practical. No other problems noted.
- Other: Zebra mussels are in abundance at the site and will only cause more problems in the future, see photo #16. Also, intake screens have been known to be heavily damaged and will need to be replaced in the near future. Remounting new intake screens, as was recently done at Markland L &D, may be a future option to consider.
- Funding Considerations: If a new lighting system were installed, it would be a high mass system. A new lighting system, public address system, and handrail system would probably all fall under a major rehab at J.T. Myers. Remounting of new intake screens would fall under regular O/M funding, unless it was lumped into a major rehab project.

5.2.2.8 Dam Inspection

<u>Dam Information</u>: The dam consists of a non-navigable gated-crest type structure 1277.5 feet long, a fixed weir section 2,239 feet long, and a concrete-capped sheet pile cut-off wall and dike 300 feet long terminating in natural submergible tainter gates l l0 feet by 32 feet high supported by concrete piers. The construction of the dam began in 1970 with completion in 1975.

5.2.2.9 Concrete Piers

<u>Concrete Piers Founded on Rock with Drilled Caissons -- Rating: 70</u>

- Alignment: The alignment of the piers looked good. No noticeable misalignment has been noted in previous periodic inspection reports.
- Cracking: Severe cracking has occurred repeatedly at the emergency bulkhead dogging a platforms, see photos #17 and #18. Most of the cracks have been epoxy injected and appear to be-holding well. However, these areas should be monitored closely to determine if conditions worsen.
- Stalls: No major spalls noted. No problems noted in previous periodic inspections.
- Stilling Basin: Could not be inspected, however, erosion problems have been noted in past periodic inspections. A diving inspection conducted in September 1986 noted erosion areas in the stilling basins at the downstream ends of piers # l 0 and # l l .

- Other: No other problems noted with the piers.
- Future Considerations/Notes: Continual monitoring and diver/dewatered inspections of the downstream stilling basins would seem to be prudent. Problems have been noted in past periodic inspections with stilling basin/river channel erosion. It has also been a problem area at other lock and dams within the district with a similar setup for the dam configuration.
- Funding Considerations: Depending on how the epoxy injected material holds, the concrete bridge piers would probably continue to be repaired under regular O/M funding. Repair work to the stilling basin would be a different issue. This would fall under major maintenance or part of a major rehab at J.T. Myers.

5.2.2.10 Dam Gates

Dam Gates Gate Type: Tainter Gates (Steel) Rating: 75

- Appearance: Overall, the tainter gates looked good, see photo #l9. No major problems were noted during the inspections or in past periodic inspections. Only the upper portion of the gates could be inspected from a distance. The paint system was in good condition for the section of the tainter gate above pool levels. The gates were last painted in 1989. Sacrificial anodes were installed in 1989 and were showing moderate deterioration at the 1991 periodic inspection.
- Corrosion: Minor pitting was noted at the last periodic inspection. Pitting was noted along the edges of the steel plates in the assemblies, along the lower edge of the upstream skin plate, and in random patterns of all skin plates normally submerged.
- Machinery: No significant problems noted.
- Other Defects: There were several side arm protective plates severely damaged due to debris and water action, see photo #20. This has been a recurring problem on the tainter gates. The plates assist in preventing damage to the trunnion beams from debris impact flushing through and around the tainter gate bays.
- Future Considerations/Notes: It was noted by the lockmaster and in previous periodic inspections that the outdated tainter gate Dam indicators are no longer useful. The obsolete system needs to be replaced with a system which will allow monitoring of more than one gate at a time with equipment maintained by the District. Also, the damaged side arm protective plates will periodically have to be replaced due to debris damage. Presently, painting of the tainter gates is done on a 15-yr, 20-yr, and 30-yr schedule depending upon which parts of the gate are typically submerged.
- Funding Considerations: Both the protective plates and painting fall under regular O/M funding. Replacement of the tainter gate indicator system would fall under a major rehab. Major rehab for J.T. Myers would also include replacement or rehabilitation of the tainter gates.

5.2.2.11 Emergency Bulkheads

Emergency Bulkheads (Steel) -- Rating: 85

- Appearance: The emergency bulkheads were being used for the dewatering of the landside chamber at the time of the inspection. The backside of the bulkheads were visible. Their general appearance looked good, see photo #21. The welds for the emergency bulkheads were recently inspected by District personnel under the fracture critical testing program. The bulkheads were in need of a few minor weld repairs which were immediately taken care of on-site. The emergency bulkheads were painted in 1989 and their appearance looked good at the last periodic inspection.

- Corrosion: Minimal surface corrosion was noted at the last periodic inspection (1991). This was not considered serious and lock personnel reported no problems involving the emergency bulkheads.
- Other: No other problems were noted.
- Future Considerations/Notes: See painting schedule as noted for the tainter gates.
- Funding Considerations: All items listed above would fall under regular O/M funding.

5.2.2.12 Dam Service Bridge

Dam Service Bridge -- Rating: 65

- Alignment: The vertical and horizontal alignment was good.
- Cracking: Significant cracking was noted at the bridge girder seats. This has been a
- constant problem over the life of the structure. It has been repaired several times since construction. The problem is due to an insufficient amount of reinforcement at the girder seats. The last repairs, made in 1991, appear to be holding well, see photos #22 and #23. These repairs consisted of a contractor epoxy injecting the cracks.
- Girders: Significant cracking of the girder through the bearing flanges has occurred. Epoxy injected repairs were made by a contractor in 1991 and appear to be holding well, see photo #24.
- Other: No other problems were noted by lock personnel.
- Future Considerations/Notes: The cracking of the girder seats has been a consistent problem with the darn structure. At the time of the inspection, the repaired cracks appeared to be holding well, however, the cracks may worsen over time. Continual monitoring will be required in the future.
- Funding Considerations: As stated for the concrete piers, typical concrete repairs will be covered under regular O/M funding. However, major repairs will be undertaken during a major rehab.

5.2.2.13 Cranes

Maintenance Bulkhead Crane -- Rating: 85

- Appearance: No problems noted.
- Machinery: No problems noted.
- Electrical: No problems noted.

- Future Considerations/Notes: Typical part replacement will be required as the crane ages. Typical items may include the replacement of the hoist cables, motors, and other associated machinery.
- Funding Considerations: Funding for replacement and/or rehab will be required in the next design life. All replacement items would typically occur at the time of a major rehab. Repair items until that point would be covered under regular O/M funding.

5.2.2.14 Fixed Weir and Cutoff Wall

Fixed Weir -- Wall Type: Concrete Gravity -- Rating: 85

- Alignment: Horizontal and vertical alignment was good, see photo #25.
- Cracking: Several surface cracks were noted while walking along the weir. No cracking of structural significance was noted.
- Spalls: Slight spalling was noted as some of the edges of the concrete. No serious spalling was noted.
- Other: Vegetation growth was noted in the rock berm, just downstream of the fixed weir. No other problems were noted during the inspection.
- Future Considerations/Notes: No serious problems have been noted on past periodic inspections in terms of the fixed weir. Considering the age of the structure, it appears to be in excellent condition.
- Funding Considerations: Any repairs will be covered by regular O/M funding. More significant concrete patching and repairs may be undertaken as part of a major rehab if necessary.

Cut-oft Wall -- Wall Type: Concrete Cap on Sheetpiles -- Rating: 85

- Alignment: No problems noted.
- Cracking: No problems noted.
- Spalls: There is a large spall at the junction of the concrete cap and the fixed weir. This has been noted in the past periodics and has not worsened.
- Other: No other problems noted during the inspection or discussion with lock personnel.
- Future Considerations/Notes: The spall occurred a number of years ago. It is not considered a problem.
- Funding Considerations: No significant repairs are anticipated for the cutoff wall. Any repairs would be covered under normal O/M funding.

5.2.2.15 Geotechnical

Streambanks Rating: 80

- Erosion Control: Wabash Island on the Indiana side has had sections of the streambank protected with riprap. Vegetation growth was noted at locations where the riprap was placed but this is not considered a serious problem. The sections which were not protected had visible signs of erosion.

- Affected Structures: As noted previously, the end monoliths of the upper and lower guide walls would benefit from additional riprap protection.
- Other Problems: No other problems noted.
- Future Considerations/Notes: Presently, the streambank protection is adequate. However, additional riprap protection will be required in the future.
- Funding Considerations: Additional riprap would be funded under normal O/M funding. This item could probably be held back until major rehab dollars are required.

5.3 GREENUP LOCKS AND DAM

Terry Shilley (ORP), David Schaaf (ORL), and Robert Taylor (ORH) visited the project site on 16 August 1995. The inspection consisted of a general walk-through of the entire project, and an extensive interview with the lockmaster, Mr. Billy Thompson.

The project has two locks. The main lock is 110’ x 1200’ and the landward auxiliary lock is 110’ x 600’. The dam is 1042 feet long (not including the hydroelectric plant). The dam has ten piers, nine gate bays and one fixed weir.

Overall, the project is in good condition. No problems were encountered that would indicate immediate concern to the safety of the structure. However, there were some problems noted that will cause concern over the next design life, i.e. 50 years, that the Ohio River Mainstem Study is attempting to address.

Project personnel indicated that the first need of this project was replacing or repairing miter gate machinery. Another major need is replacing all hydraulic equipment with electric motors. Other concerns, problems and issues will be addressed throughout this report.

From the time period 1985-1995, there was an increase from 4,867 to 6,313 in the number of tows to lock through at Greenup, an increase of approximately 30%. Over the same period, the increase in tonnage went from 41,139 to 67,573 kilotons, an increase of approximately 64%. Recreational traffic from 1989 to 1995 increased approximately 139% to 1,009 pleasure craft lockages in 1995. Although the traffic increases have been significant, many projects along the system already handle the amount of traffic that Greenup will not encounter until about the year 2050.

Several issues at Greenup Locks make it the most critical lock on the Ohio River within the Huntington District. The condition of the project is worse than any other in ORH due to its age and traffic frequency. The pansy beds have been and area of structural concern for some time, and since the addition of the highway bridge to the dam piers, significant deterioration and problems have occurred on the dam. All the miter gates are less than good condition and require replacement within 10 years. Also, traffic projections for Greenup exceed even some of the downstream locks which typically have more lockages. All these facts when taken together make Greenup the most important maintenance concern for the district.

5.3.1 Project Personnel Interview

Personnel Interviewed: Billy Thompson (Lockmaster)
Date: 16 August 1995

Several issues were discussed with Mr. Thompson about the condition of Greenup Locks and Dam. Mr. Thompson has been lockmaster at the project for five years. The following is a brief overview of important items discussed during the interview.

- Emergency Gates: The emergency gates are two leaf vertical lift gates. Although some screens are missing on the gates, project personnel indicated that these gates are in good condition. Cables for the gates were inspected and filmed in 1994 and were found to be in good condition. Lastly, project personnel indicated that there was no silt problem with the gates.
- Generator: The project has recently received a new generator and new incoming power.
- Handrailing: The project is currently replacing chains with handrails. However, this is ongoing on the middle wall only.
- Hydraulics: Project personnel would like to see all hydraulics replaced with electric motors. Mr. Thompson considers this one of the project's bigger needs.
- New Locks: Mr. Thompson noted that there was a need at the project for an additional 1200' lock.
- Miter Gates: Several problems were noted with the miter gates. In the main chamber, the downstream face of the skin plate on the downstream gate often stays wet. The downstream gate also vibrates while the chamber is filling to a certain head, indicating a bad bottom seal. The upstream main chamber gate vibrates when closing. Mr. Thompson also noted that repair of miter gate machinery is the first priority of the project. He also noted that piping in the galleries rattles when the miter gates are being closed.
- Lighting: Lighting at the project is adequate. However, the project is scheduled to receive new highmast lighting.
- Cameras**.** The project currently operates without the use of cameras.
- Emergency Bulkheads: Project personnel noted that the seals are bad on the emergency bulkheads.
- Poiree Dam: Mr. Thompson has never seen the poiree dam in place. He also noted that the poiree dam may have been removed when the gate sills at the project were revised.
- Zebra Mussels: The project has a few zebra mussels, but they do not cause any major problems.
- Crossovers: Mr. Thompson noted some leakage in the crossovers.
- Cranes: The bulkhead crane has 35 year old cables. Mr. Thompson stated that these cables should be replaced every 20 years. The bantam crane is unsafe and is not being used.
- Other Issues: Mr. Thompson would like PLC's installed at the project. The lower approach is dredged yearly. Ice and drift are occasional problems for the project. The intake screens were noted to be in good condition. Insulation for electric cables at the project is starting to deteriorate. There are two mooring cells upstream. The lockmaster would like to have two more downstream. The main chamber was dewatered last in 1991. Lastly, the current staff at the project is 15 full-time employees and 2 seasonal employees. Mr. Thompson stated that he could use more.

5.3.2 Project Personnel Interview

Site: Greenup Locks and Dam
Location: 341.0 river miles below Pittsburgh, PA near Greenup, KY
Date of Inspection: 16 August 1995
Inspectors: T. Shilley: ORP, Taylor: ORH, and D. Schaaf: ORL

5.3.2.1 Rating Guidelines for All Components

VALUE	CONDITION	DESCRIPTION
85-100	Excellent	No noticeable defects. Aging/wear may be visible.
70-84	Very Good	Only minor deterioration or defects noticeable.
55-69	Good	Deterioration noted but function not significantly affected.
40-54	Fair	Moderate deterioration; function slightly affected.
25-39	Poor	Serious deterioration; function is inadequate
10-24	Very Poor	Extensive deterioration; barely functional.
1-9	Failed	No longer functional, needs major repair or replacement.

5.3.2.2 Lock Inspection

Lock Information: The two adjacent parallel lock chambers are located along the Kentucky shore. The main lock, riverside, has clear dimensions of 110 x 1200 feet and the auxiliary lock has clear dimensions of 110 x 600 feet. The lift is 30 feet at normal pool levels. Two sets of hydraulically operated steel miter gates are provided for each lock. Double-leaf submergible vertical emergency gates are located immediately upstream of the upper miter gates in each chamber and are operated with electrical hoists. The construction of the locks and guide/guard walls began in October 1955 with completion in April 1959. The average age of the lock and guide/guard wall concrete is approximately 38 years.

5.3.2.3 Wall Monoliths

Land Wall Monoliths -- Wall Type: Concrete Gravity on Rock -- Rating: 75

- Alignment: No problems noted.
- Cracking: No significant cracks noted.
- Spalls: Spalling was present around Chamber Marker 450 on the chamber face.
- Other: Grating was warped, creating a tripping hazard.

Middle Wall Monoliths -- Wall Type: Concrete Gravity on Rock -- Rating: 55

- Alignment: A vertical misalignment of 1/4" to 1/2" between monoliths M1 and M2 was noted as shown in photo #1 and photo #2. Also, a vertical misalignment of 1/2" to 3/4" between M33 and M34 was noted as well. This settlement of the end monoliths (M1 and M34) appeared to be old without any recent movement.
- Cracking: Monoliths M8 and M25 have large vertical cracks which appear to run from the top of the monolith to the culvert as seen in the culvert bulkhead recesses (see photo's #3 and #4). Monoliths M8 and M20 through M24 were anchored horizontally in 1976 to pin the monoliths with vertical cracks from the "pansy beds" together. A large vertical crack was noted on the auxiliary chamber face of Monolith M17 as shown in photo #5.
- Spalls: Spalls were noted on the landward face at the M1-M2 monolith joint and in the culvert valve machinery recess at the M6-M7 monolith joint. Also, there was spalling around the vertical crack in the culvert valve bulkhead recess of Monolith M8. The emergency gate trash guard guide concrete was cracked and spalling.
- Other: The grating at Monolith M25 was warped, creating a tripping hazard as shown in photo #6. The concrete slabs over the "pansy beds" have settled up to 4" (see photo's #7-#9). There was considerable surface deterioration of the concrete at monoliths M1, M2, M26, and M34 and in the miter gate recesses as shown in photo #10 of Monolith Joint M1/M2.

River Wall Monoliths -- Wall Type: Concrete Gravity on Rock -- Rating: 60

- Alignment: No problems noted.
- Cracking: Tight cracks were found in the culvert valve recesses of monoliths R47 and R56. Larger cracks (about 1/8") were seen in the culvert bulkhead recesses of R46 and R57. Large vertical cracks were noted in the main lock face at Markers 200, 240,330, 560, 615, and 735 (see photo's #11-#13). The downstream miter gate recess of Monolith R29 had an 8' long horizontal hairline crack 3" below the monolith surface.
- Spalls: A spall was noted at Marker 985 on the lock face.
- Other: The concrete surface exhibited numerous aggregate popouts as shown in photo #14.

5.3.2.4 Guide/Guard Walls

Upper Guide (Landside) Wall -- Wall Type: Concrete Gravity on Steel H-Piles -- Rating: 75

- Alignment: The upper end of the wall was hit by a barge in February 1989, which caused the upper monoliths to move landward differentially such that several of the joints are misaligned. The greatest movement was in the end monolith, L37, which moved 0.28 ft. The movement appears to have stabilized. Photo #15 and photo #16 show the misalignment at Monolith Joint L36/L37.
- Cracking: No significant cracking observed.
- Spalls: Several random spalls and gouges on vertical face were noticed, e.g., along a lift joint from Marker 150 to 200 (see photo #17). On the landward face at monolith joint L36-37 were two patched areas that appeared to be loose and ready to fall as shown in photo #18.
- Other: No other problems noted.

Upper Guard (Riverside) Wall -- Wall Type: Concrete Wall on Tremie-filled Cells -- Rating: 75

- Alignment: No significant misalignment noted.
- Cracking: No significant cracking noted.
- Spalls: No significant spalls noted.
- Other: Small aggregate popouts on the surface were noted.
- Future Considerations/Notes: Consideration should be given to resurfacing the area.

Lower Guide Wall -- Wall Type: Concrete Gravity on Rock -- Rating: 80

- Alignment: No significant misalignment noted.
- Cracking: No significant cracking noted.
- Spalls: No significant spalls noted.

Lower Guard Wall -- Wall Type: Concrete Wall on Tremie-filled Cells -- Rating: 70

- Alignment: No problems noted.
- Cracking: No serious cracking noted.
- Spalls: Monolith R14 had a 3-ft long by 6-in. wide spall on the top surface. Large spalls were also noted on the lock face at Markers 110 and 150.
- Other: Only one chain is provided for safety along the top of the wall. Also, there were numerous small aggregate popouts on the top surface.

5.3.2.5 Lock Gates

Landside Chamber Lock Gates -- Gate Type: Horizontally Framed Miter Gates -- Rating: 50

- Appearance: The gates need to be painted and several timber fenders replaced. The diagonal protection exhibited dents as shown in photo #19 of the downstream landwall leaf.
- Anchorage: No significant problems were noted.
- Leakage: Considerable leakage was observed at the quoins of both upper and lower miter gates (photo #20), and at the miter block of the downstream gate (photo #21).
- Machinery: Both gates exhibited jerky motion and apparent play in the linkages during operation.
- Sill: Sills were submerged during inspection and could not be seen. No mention of sill condition in latest Periodic Inspection.

Riverside Chamber Lock Gates -- Gate Type: Horizontally Framed Miter Gates -- Rating: 50

- Appearance: The gates need painted and a number of timber fenders need replaced as shown in photo #22. The skin plate of the downstream miter gate had numerous dents (see photo #23).

Also, the flanges of the horizontal girders near the quoin end of the downstream miter gate middle leaf were damaged as shown in photo #24. The lockmaster reported that the skin plate of the downstream miter gate was wet on the downstream side, suggesting that there was some leakage through the plate.

- Anchorage: No significant problems were noted.
- Leakage: Downstream gates have heavy leakage at the miter and quoin blocks (photo #25), while the upper gate has heavy leakage at the quoins (photo #26).
- Machinery: The downstream middle wall rack guide rollers exhibited some corrosion as shown in photo #27.
- Sill: Sills were submerged during inspection and could not be seen.
- Other: The downstream miter gate vibrates as the chamber fills. The handrail posts at the upstream gate are very loose. The upstream middle wall leaf vibrates while closing. The emergency gates were reported to be in good condition, except for some screens missing. The emergency gate wire ropes were inspected and filmed in 1994 and found to be in good condition.
- Future Considerations/Notes: Last dewatering of the main lock was in 1991. The lockmaster considers replacement/repair of the miter gate machinery their highest priority. The lockmaster sees a real need for an additional 1200-ft lock.

5.3.2.6 Culvert Valves

Landside Chamber Culvert Valves -- Type: Reverse Tainter Valves -- Rating: 70

- Appearance: The culvert valve area was not dewatered for the inspection.
- Machinery: No significant problems were noted for the valve machinery.
- Other: Refer to interview with project personnel for vale maintenance cycle.

Riverside Chamber Culvert Valves -- Type: Reverse Tainter Valves -- Rating: 75

- Appearance: The culvert valve area was not dewatered for the inspection.
- Machinery: No significant problems were noted for the valve machinery.
- Other: The filling valves in the middle wall makes a noise and jerks under a high head/low tailwater loading.
- Future Considerations/Notes: These valves have an old U-bolt design trunnion design in which the bolts must be replaced periodically.

5.3.2.7 Miscellaneous Items

- Control Structures: In general, looked good.
- Electrical/Lighting: The existing lighting is adequate, but high-mast lighting is expected to be added in the near future. There are no cameras on site. The generator and incoming power lines were recently replaced. The lockmaster would like to have PLC's to operate the equipment.
- Equipment: Project personnel reported dissatisfaction with hydraulic equipment. The piping is old and uses hydraulically operated flow control valves. They would like to see the hydraulics replaced with electric motors.

- Safety: Need to install OSHA approved handrails throughout project to improve safety for lock personnel. Only the chains on the middle wall were being replaced with handrails.
- Other: Gage houses do not work. Lower approach must be dredged annually. Ice is occasionally a problem. Debris is a problem during open river. There is some leakage in the lock crossovers. There are two mooring cells upstream of the project, but none downstream.

5.3.2.8 Dam Inspection

Dam Information: The dam is a non-navigable gated-crest type structure 1,042 feet long (not including the hydropower plant). Nine nonsubmergible steel tainter gates span 100 feet between 14-ft wide piers to provide a damming height of 35 feet above the concrete sills. There are a total of 10 concrete piers, all founded on firm rock. A concrete bridge structure supports a rail-mounted crane used for transporting and placing the emergency closure bulkhead, and for servicing the gates and hoist machinery. Additionally, the dam piers support a concrete public highway bridge. Construction of the dam began in 1958 and was completed in 1962.

5.3.2.9 Concrete Piers

Concrete Piers -- Type: Concrete on Rock -- Rating: 75

-
- Alignment: No problems noted.
- Cracking: Pier 1 had random cracks on the 3rd floor that had been sealed. Piers 2, 4, 6, and 7 had cracks at the dogging platform, running between the bulkhead recesses (see photo’s #28 and #29). Pier 8 had a crack in the pier supporting the crane bridge. Piers 3 and 4 had longitudinal cracks under the housing support beams as shown in photo #30 of Pier no. 3. Most of the piers exhibited diagonal cracks in the downstream sidewalls.
- Spalls: Pier 4 had spalls at the stairs of the dogging platform (see photo #31). Pier 5 had a spall on the corner of the bulkhead recess (just above the upstream pool level) as shown in photo #32. The upstream end of pier 9 was spalled at about the elevation of the dogging platform.
- Stilling Basin: Not dewatered, by no problems noted in past diver inspections.
- Other: Piping on bridge girders needed paint as shown in photo #33.

5.3.2.10 Dam Gates

Dam Gates -- Gate Type: Tainter Gates -- Rating: 75

- Appearance: The gates generally looked good. They were in the process of being painted during the site visit. Several of the sidearm covers were damaged badly or completely missing as shown in photo #34.
- Corrosion: The gates were being painted.
- Machinery: All machinery appeared to be in good working order, except for a reported brake failure at Gate 5.

5.3.2.11 Emergency Bulkheads

Emergency Bulkheads -- Rating: 75

- Appearance: Bulkheads were in need of painting as shown in photo #35.
- Corrosion: General rust.
- Other: Seals leaked.

5.3.2.12 Dam Service Bridge

Dam Service Bridge -- Rating: 75
Crane -- Rating: 40
Bantam Crane -- Rating: 5

- Alignment: No problems noted.
- Cracking: No problems noted.
- Girders: Random surface cracks were sealed. Downstream girder at Pier 4 had a small crack.
- Crane: Crane needs painting. Crane rail expansion joints are not compatible. Hoist cables are 35 years old while the manufacturer's recommended a life of 20 years. The Bantam piggy-back crane is no longer safe and is not used.
- Machinery: The crane machinery is outdated and obsolete.
- Electrical: The power supply lines are out of alignment such that a person must stand along the line with a stick so that the crane can pass (see photo #36). The insulation on the electric cables is very old and starting to break off.
- Future Considerations/Notes: The piggyback crane in inoperable and needs replaced.

5.3.2.13 Fixed Weir

Fixed Weir --Wall Type: Tremie-Filled Cells Tying into a Hydropower Plant -- Rating: 60

- Alignment: No problems noted.
- Cracking: The upstream cell had large radial cracks as shown in photo #37.
- Spalls: The cells where the sheet piling had been removed were terribly spalled (see photo #38).

5.3.2.14 Geotechnical

Streambanks -- Rating: 80

- Problems: None noted by lockmaster or previous Periodic Inspection.
- Future Considerations/Notes: No geotechnical problems were noted that could impair the operation of the project.

5.3.3 General Inspection Results

Site: Greenup Locks and Dam
Location: 341.0 river miles below Pittsburgh, PA near Greenup, KY
Date of Inspection: 16 August 1995
Inspectors: T. Shilley (ORP), R. Taylor (ORH), D. Schaaf (ORL)

5.3.3.1 Rating Guidelines for All Components

VALUE	CONDITION	DESCRIPTION
85-100	Excellent	No noticeable defects. Aging/wear may be visible.
70-84	Very Good	Only minor deterioration or defects noticeable.
55-69	Good	Deterioration noted but function not significantly affected.
40-54	Fair	Moderate deterioration; function slightly affected.
25-39	Poor	Serious deterioration; function is inadequate
10-24	Very Poor	Extensive deterioration; barely functional.
1-9	Failed	No longer functional, needs major repair or replacement.

5.3.3.2 Lock Inspection

Lock Information: The two adjacent parallel lock chambers are located along the Kentucky shore. The main lock, riverside, has clear dimensions of 110 x 1200 feet and the auxiliary lock has clear dimensions of 110 x 600 feet. The lift is 30 feet at normal pool levels. Two sets of hydraulically operated steel miter gates are provided for each lock. Double-leaf submergible vertical emergency gates are located immediately upstream of the upper miter gates in each chamber and are operated with electrical hoists. The construction of the locks and guide/guard walls began in October 1955 with completion in April 1959. The average age of the lock and guide/guard wall concrete is approximately 38 years.

5.3.3.3 Wall Monoliths

Land Chamber Wall Monoliths -- Wall Type: Concrete Gravity On Rock – Rating: 75

- Alignment: No problems noted.
- Cracking: No significant cracks noted.
- Spalls: Spalling was present around Chamber Marker 450 on the chamber face.
- Other: Grating was warped, creating a tripping hazard.
- Future Considerations/Notes:

Middle Chamber Wall Monoliths -- Wall Type: Concrete Gravity on Rock Rating: 55

- Alignment: A vertical misalignment of 1/4" to 1/2" between monoliths M1 and M2 was noted. Also, a vertical misalignment of 1/2" to 3/4" between M33 and M34 was noted as well. This settlement of the end monoliths (M1 and M34) appeared to be old without any recent movement.
- Cracking: Monoliths M8 and M25 have large vertical cracks which appear to run from the top of the monolith to the culvert as seen in the culvert bulkhead recesses. Monoliths M8 and M20 through M24 were anchored horizontally in 1976 to pin the monoliths with vertical cracks from the "pansy beds" together. A large vertical crack was noted on the auxiliary chamber face of Monolith M17.
- Spalls: Spalls were noted on the landward face at the M1-M2 monolith joint and in the culvert valve machinery recess at the M6-M7 monolith joint. Also, there was spalling around the vertical crack in the culvert valve bulkhead recess of Monolith M8. The emergency gate trash guard guide concrete was cracked and spalling.
- Other: The grating at Monolith M25 was warped, creating a tripping hazard. The concrete slabs over the "pansy beds" have settled up to 4". There was considerable surface deterioration of the concrete at monoliths M1, M2, M26, and M34 and in the miter gate recesses.
-
- Future Considerations/Notes:

River Chamber Wall Monoliths: Wall Type: Concrete Gravity on Rock -- Rating: 60

- Alignment: No problems noted.
- Cracking: Tight cracks were found in the culvert valve recesses of monoliths R47 and R56. Larger cracks (about 1/8") were seen in the culvert bulkhead recesses of R46 and R57. Large vertical cracks were noted in the main lock face at Markers 200, 240,330, 360, 615, and 735. The downstream miter gate recess of Monolith R29 had an 8' long horizontal hairline crack 3" below the monolith surface.
- Spalls: A spall was noted at Marker 985 on the lock face.
- Other: The concrete surface exhibited numerous aggregate popouts.
- Future Considerations/Notes:

5.3.3.4 Guide/Guard Walls

Upper Guide (Landside) Wall -- Wall Type: Concrete Gravity on Steel H-Piles -- Rating: 75

- Alignment: The upper end of the wall was hit by a barge in February 1989, which caused the upper monoliths to move landward differentially such that several of the joints are misaligned. The greatest movement was in the end monolith, L37, which moved 0.28 ft. The movement appears to have stabilized.
- Cracking: No significant cracking observed.

- Spalls: Several random spalls and gouges on vertical face were noticed, e.g., along a lift joint from Marker 150 to 200. On the landward face at monolith joint L36-37 were two patched areas that appeared to be loose and ready to fall.
- Other: No other problems noted.
- Future Considerations/Notes:

<u>Upper Guard (Riverside) Wall -- Wall Type: Concrete Wall on Tremie-filled Cells -- Rating: 75</u>

- Alignment: No significant misalignment noted.
- Cracking: No significant cracking noted.
- Spalls: No significant spalls noted.
- Other: Small aggregate popouts on the surface were noted.
- Future Considerations/Notes: Consideration should be given to resurfacing the area.

<u>Lower Guide Wall -- Wall Type: Concrete Gravity on Rock -- Rating: 80</u>

- Alignment: No significant misalignment noted.
- Cracking: No significant cracking noted.
- Spalls: No significant spalls noted.
- Other:
- Future Considerations/Notes:

<u>Lower Guard Wall -- Wall Type: Concrete Wall on Tremie-filled Cells--Rating: 70</u>

- Alignment: No problems noted.
- Cracking: No serious cracking noted.
- Spalls: Monolith R14 had a 3-ft long by 6-in. wide spall on the top surface. Large spalls were also noted on the lock face at Markers 110 and 150.
- Other: Only one chain is provided for safety along the top of the wall. Also, there were numerous small aggregate popouts on the top surface.
- Future Considerations/Notes:

5.3.3.5 Lock Gates

<u>Landside Chamber Lock Gates -- Gate Type: Horizontally Framed Miter Gates -- Rating: 50</u>

- Appearance: The gates need to be painted and several timber fenders replaced. The diagonal protection exhibited dents.
- Anchorage: No significant problems were noted.
- Leakage: Considerable leakage was observed at the quoins of both upper and lower miter gates, and at the miter block of the downstream gate.

- Machinery: Both gates exhibited jerky motion and apparent play in the linkages during operation.
- Sill: Sills were submerged during inspection and could not be seen. No mention of sill condition in latest Periodic Inspection.
- Other:
- Future Considerations/Notes:

Riverside Chamber Lock Gates -- Gate Type: Horizontally Framed Miter Gates -- Rating: 50

- Appearance: The gates need painted and a number of timber fenders need replaced. The skin plans of the downstream miter gate had numerous dents. Also, the flanges of the horizontal girders near the quoin end of the downstream miter gate middle leaf were damaged. The lockmaster reported that the skin plate of the downstream miter gate was wet on the downstream side, suggesting that there was some leakage through the plate.
- Anchorage: No significant problems were noted.
- Leakage: Downstream gates have heavy leakage at the miter and quoin blocks, while the upper gate has heavy leakage at the quoins.
- Machinery: The downstream middle wall rack guide rollers exhibited some corrosion.
- Sill: Sills were submerged during inspection and could not be seen.
- Other: The downstream miter gate vibrates as the chamber fills. The handrail posts at the upstream gate are very loose. The upstream middle wall leaf vibrates while closing. The emergency gates were reported to be in good condition, except for some screens missing. The emergency gate wire ropes were inspected and filmed in 1994 and found to be in good condition.
- Future Considerations/Notes: Last dewatering of the main lock was in 1991. The lockmaster considers replacement/repair of the miter gate machinery their highest priority. The lockmaster sees a real need for an additional 1200-ft lock.

5.3.3.6 Culvert Valves

Landside Chamber Culvert Valves--Type: Reverse Tainter Valves--Rating: 70

- Appearance:
- Machinery:
- Other:
- Future Considerations/Notes:

Riverside Chamber Culvert Valves Type: Reverse Tainter Valves -- Rating: 75

- Appearance:
- Machinery:
- Bulkheads:

- Other: The filling valves in the middle wall makes a noise and jerks under a high head/low tailwater loading.
- Future Considerations/Notes: These valves have an old U-bolt design trunnion design in which the bolts must be replaced periodically.
- Miscellaneous Items:
- Control Structures: In general, looked good.
- Electrical/Lighting: The existing lighting is adequate, but high-mast lighting is expected to be added in the near future. There are no cameras on site. The generator and incoming power lines were recently replaced. The lockmaster would like to have PLC's to operate the equipment.
- Equipment: Project personnel reported dissatisfaction with hydraulic equipment. They would like to see the hydraulics replaced with electric motors.
- Safety: Need to install OSHA approved handrails throughout project to improve safety for lock personnel. Only the chains on the middle wall were being replaced with handrails.
- Other: Gage houses do not work. Lower approach must be dredged annually. Ice is occasionally a problem. Debris is a problem during open river. There is some leakage in the lock crossovers. There are two mooring cells upstream of the project, but none downstream.

5.3.3.7 Dam Inspection

Dam Information: The dam is a non-navigable gated-crest type structure 1,042 feet long (not including the hydropower plant). Nine nonsubmergible steel tainter gates span 100 feet between 14-ft wide piers to provide a damming height of 35 feet above the concrete sills. There are a total of 10 concrete piers, all founded on firm rock. A concrete bridge structure supports a rail-mounted crane used for transporting and placing the emergency closure bulkhead, and for servicing the gates and hoist machinery. Additionally, the dam piers support a concrete public highway bridge. Construction of the dam began in 1958 and was completed in 1962.

5.3.3.8 Concrete Piers

Concrete Piers -- Type: Concrete on Rock -- Rating: 75

- Alignment: No problems noted.
- Cracking: Pier 1 had random cracks on the 3rd floor that had been sealed. Piers 2, 4, 6, and 7 had cracks at the dogging platform, running between the bulkhead recesses. Pier 8 had a crack in the pier supporting the crane bridge. Piers 3 and 4 had longitudinal cracks under the housing support beams. Most of the piers exhibited diagonal cracks in the downstream sidewalls.
- Spalls: Pier 4 had spalls at the stairs of the dogging platform. Pier 5 had a spall on the corner of the bulkhead recess (just above the upstream pool level). The upstream end of pier 9 was spalled at about the elevation of the dogging platform.
- Stilling Basin:
- Other: Piping on bridge girders needed paint.
- Future Considerations/Notes:

5.3.3.9 Dam Gates

Dam Gates -- Gate Type: Tainter Gates -- Rating: 75

- Appearance: The gates generally looked good. They were in the process of being painted during the site visit. Several of the sidearm covers were damaged badly or completely missing.
- Corrosion: The gates were being painted.
- Machinery: All machinery appeared to be in good working order, except for a reported brake failure at Gate 5.
- Other Defects:
- Future Considerations/Notes:

5.3.3.10 Emergency Bulkheads

Emergency Bulkheads -- Rating: 75

- Appearance: Bulkheads were in need of painting.
- Corrosion: General rust.
- Other: Seals leaked.
- Future Considerations/Notes:

5.3.3.11 Dam Service Bridge

Dam Service Bridge -- Rating: 75
Crane -- Rating: 40
Bantam Crane -- Rating: 5

- Alignment: No problems noted.
- Cracking: No problems noted.
- Girders: Random surface cracks were sealed. Downstream girder at Pier 4 had a small crack.
- Crane: Crane needs painting. Crane rail expansion joints are not compatible. Hoist cables are 35 years old while the manufacturer's recommended a life of 20 years. The Bantam piggy-back crane is not longer safe and is not used.
- Machinery: The crane machinery is outdated and obsolete.
- Electrical: The power supply lines are out of alignment such that a person must stand along the line with a stick so that the crane can pass. The insulation on the electric cables is very old and starting to break off.
- Other:
- Future Considerations/Notes:

5.3.3.12 Fixed Weir

Fixed Weir -- Wall Type: Tremie-filled cells tying into a hydropower plant -- Rating: 60

- Alignment: No problems noted.
- Cracking: The upstream cell had large radial cracks .
- Spalls: The cells where the sheet piling had been removed were terribly spalled.
- Other:
- Future Considerations/Notes:

5.3.3.13 Geotechnical

Streambanks -- Rating: 80

- Erosion Control:
- Affected Structures:
- Other Problems: None noted by lockmaster or previous Periodic Inspection.
- Future Considerations/Notes: No geotechnical problems were noted that could impair the operation of the project.

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SECTION 6

LOCK AND DAM RISK AND RELIABILITY MODELING

This section describes the effort involving the engineering and economic modeling of major lock and dam components for ORMSS. The purpose of engineering reliability modeling is to determine the long-term performance of major lock and dam components. Additionally, the analysis predicts the consequences of unsatisfactory performance from both a navigation delay standpoint as well as repair cost standpoint as structures age and see increase operating cycles. The engineering reliability and economic risk assessment of these components plays an important role in the development of net benefits for the various alternatives being considered.

6.1 COMPONENTS REQUIRING RELIABILITY ANALYSIS

The initial effort of the overall reliability assessment of the lock and dam was to determine which components should have reliability analysis conducted on them. Since there are several components that can cause disruption of navigation service, a process of eliminating "minor" components had to be developed. Therefore, the team developed a two-phase screening process that eliminated several minor components from consideration for reliability analyses. This screening process also made the overall effort manageable in terms of available funding and time constraints.

6.1.1 Selection of Components

The initial effort on the ORMSS was for a team of engineers, one from each of the three participating districts, to go out and inspect every lock and dam on the Ohio River to determine their condition relative to one another. Included in this effort was interviewing personnel at the project site in order to get as much information as possible. This group was kept as consistent as possible in order to have a fair rating of the locks relative to one another. The second step was for the same group of engineers to review the plans and Periodic Inspection Reports for each of the sites. From this effort, an initial master list of 146 components was developed for screening. This list was developed to represent all the sites on the Ohio River. The list was screened in two stages. The first phase screening process was used to investigate the relative importance of a component in terms of the overall lock operation. The second phase screening investigated the overall importance of the component from both a site specific and an overall Ohio River systems standpoint.

First Phase Screening

A sample of the original list of lock components, shown in Table 6.1.1.A, was screened based upon their relative importance to the overall operation of the lock. A multi-district, multi-discipline team of engineers screened the original list of components as part of the first phase. If a component was considered non-essential or could be repaired as part of routine maintenance, it was screened out during the first phase. If any of the following reasons were applicable, the component was screened out first phase:

Redundancy. The component's function could be accomplished by other means or there are numerous components that would have to perform unsatisfactorily at the same time to be considered a significant problem. An example would be that line hooks could be used instead of check posts if necessary.

Table 6.1.1.A Sample of Master List of Components for Reliability Screening

Item #	Component	Component Use	Discipline	Screened Out	Reason for Screen Out
64	Chamber Monolith Stability	Lock	Struct/Geotech	No	
65	Miter Gate Monolith Stability	Lock	Struct/Geotech	No	
66	Concrete Horizontal Surfaces	Lock/Dam	Structural	No	
67	Guardwall/Guidewall Stability	Lock	Struct/Geotech	No	
68	Fixed Weir Stability	Dam	Struct/Geotech	No	
69	Sheet Pile Cellular Structures Stability	Lock	Struct/Geotech	No	
70	Pile Founded Structures Stability	Lock/Dam	Struct/Geotech	No	
71	Dam Pier Stability	Dam	Struct/Geotech	No	
72	Mass Concrete	Lock/Dam	Structural	No	
73	Overflow Spillway Stability	Dam	Struct/Geotech	No	
74	Miter Gate Sill Stability	Lock	Struct/Geotech	No	
75	Dam Gate Sill Stability	Dam	Struct/Geotech	No	
76	Retaining Wall Stability	Lock/Dam	Struct/Geotech	No	
77	Air Conditioning Units	Miscellaneous	Mech./Elec.	Yes	Not considered critical to operation of lock and dam.
78	Heating/Furnace Units	Miscellaneous	Mech./Elec.	Yes	Not considered critical to operation of lock and dam.
79	Raw Water Pump	Miscellaneous	Mech./Elec.	Yes	Handled through normal maintenance.
80	Strainer	Miscellaneous	Mech./Elec.	Yes	Handled through normal maintenance.
81	Bubbler System	Lock/Dam	Mech./Elec.	Yes	Redundant, other means available to serve purpose.
82	Fuel Oil Transfer Pump	Miscellaneous	Mech./Elec.	Yes	Handled through normal maintenance.
83	Water Heaters	Miscellaneous	Mech./Elec.	Yes	Not considered critical to operation of lock and dam.
84	Exhaust Fans	Miscellaneous	Mech./Elec.	Yes	Not considered critical to operation of lock and dam.
85	Service Building Crane	Maintenance	Mech./Elec.	Yes	Not considered critical to operation of lock and dam.
86	Piggy Back Crane	Maintenance	Mech./Elec.	Yes	Not considered critical to operation of lock and dam.
87	Dam Elevator Mechanical	Dam	Mech./Elec.	Yes	Redundant, other means available to serve purpose.
88	Closed Circuit TV System	Lock/Dam	Mech./Elec.	Yes	Redundant, other means available to serve purpose.
89	Batteries	Miscellaneous	Mech./Elec.	Yes	Not considered critical to operation of lock and dam.
90	Cathodic Protection	Lock	Mech./Elec.	Yes	Handled through normal maintenance.
91	Anodes	Lock/Dam	Mech./Elec.	Yes	Handled through normal maintenance.
92	Siren System/Air Whistle	Lock/Dam	Mech./Elec.	Yes	Not considered critical to operation of lock and dam.
93	Panel Heater	Miscellaneous	Mech./Elec.	Yes	Handled through normal maintenance.
94	Control Building Mechanical	Lock/Dam	Mech./Elec.	Yes	Handled through normal maintenance.
95	Control Building Electrical	Lock/Dam	Mech./Elec.	Yes	Handled through normal maintenance.
96	Service Building Misc. Mechanical	Maintenance	Mech./Elec.	Yes	Handled through normal maintenance.
97	Service Building Misc. Electrical	Maintenance	Mech./Elec.	Yes	Handled through normal maintenance.

Non-critical. The component was not considered critical to the overall operation of the lock. An example is wall armor along monolith vertical face.

Routine Maintenance. If the component were to perform unsatisfactorily in any manner, it would always be repaired as part of normal maintenance. An example would be handrails, grating, etc.

Reliable Component. The likelihood of unreliable performance was considered remote. An example is culvert bulkhead sill stability.

Any components that did not fall into one of these screening criteria were screened again during the second phase screening process. Out of 146 total initial components, a total for all Ohio River locks, 60 survived the first screening phase. Since there was not enough funding or time to warrant reliability models for 60 different components, the first phase survivors were screened a second time during the second phase. This phase is described in the next section.

Second Phase Screening

All components that survived the first phase of screening were subjected to a second level screening. The second phase screening process was developed in an attempt to incorporate the importance of a particular component not only on a site-specific basis, but also on a systems basis in relation to other lock and dams on the Ohio River. Sixty lock components survived the first phase screening process out of 146 initial components. These 60 survivors were next rated by the same multi-district/multi-discipline team of engineers on a scale of 1 to 3 based upon six categories: *System Number, Component Site Consequence, Component Site Cost, Component System Cost, System Consequence, and Likelihood of Problems*. Some of the categories based their results upon answering questions about the performance of the component. A description of each category is detailed below.

Ranking	Description
1.0	Low, No, Minor
2.0	Medium, Average
3.0	High, Yes, Major

System Number. Number of sites of locations where this component was present within the Ohio River Main Stem lock and dam system.

Component Site Consequence. From a site-specific standpoint, how would navigation traffic be directly and immediately affected by the unsatisfactory performance of the component. Is there a lack of redundancy for this component from a site-specific standpoint?

Component Site Cost. From a site-specific standpoint, does the total number of the components reflect a major rehab/replacement cost relative to the site?

Component System Cost. From an overall system standpoint, does the total number of this component reflect a significant rehabilitation/replacement cost on the entire system?

System Consequence. From an overall standpoint, if this component were to perform unsatisfactorily, would navigation be impacted significantly?

Likeliness of Problems. Is it likely that the component would need repairs based upon past performance or suspected degradation?

A special ranking system was developed to assist in ranking the system categories: *System Consequence*, *Component System Cost,* and *System Number*. The ranking system is shown in Figure 6.1.1.A on the following sheet. The values that were computed from that sheet were input into the overall ranking sheet for the three categories for the Phase 2 rating, as shown in Table 6.1.1.B.

The results for each of the six categories were added together to determine a final ranking. After reviewing the overall rankings, it was determined that there was a general break in the rankings for components around the 12-13 range. Therefore, the engineering team decided that components which had a phase 2 overall ranking of 13 or above (out of a maximum of 18), would have reliability analyses completed for them. The results of the Phase 2 screening are depicted in Table 6.1.1.B.

There were a total of 20 components that survived both the first and second phase screenings. The components are summarized below:

List of Components for Reliability Model Development

1. Horizontally-framed Miter Gates
2. Vertically-framed Miter Gates
3. Miter Gate Anchorage
4. Reverse Tainter Gate Culvert Valves
5. Butterfly Valves
6. Reverse Tainter Culvert Valve Anchorage
7. Chamber Monolith Stability
    a. Unanchored Lock Wall Monoliths
    b. Anchored Lock Wall Monoliths
8. Miter Gate Monolith Stability
9. Guard/Guide Wall Stability
    a. Gravity Structures
    b. Pile-Founded
10. Miter Gate Sill Stability
    a. Unanchored Sills
    b. Anchored Sills
11. Hydraulic Power System (Mechanical)
12. Power and Control Equipment (Electrical)
13. Dam Tainter Gates
14. Dam Tainter Gate Anchorage
15. Dam Roller Gates
16. Dam Vertical Lift Gates
17. Dam Pier Stability
18. Fixed Weir Stability
19. Dam Gate Sill Stability
20. Sheet Pile Cellular Structure Stability

FIGURE 6.1.1.A. Phase 2 Ranking Criteria for System Categories

	Individual Lock and Dam Component Data							1994 Traffic Information		
	Miter Gates		Culvert Valves		Dam Gates			Individual Site		
Project Site	**Hrz. Framed**	**Vert. Framed**	**Butterfly**	**R. Tainter**	**Roller**	**Tainter**	**Vertical Lift**	**'94 kilotons**	**% Total**	**Conseq. Rank**
Emsworth	2	2	44	-	-	-	13	24,272	2.24%	**1.0**
Dashields	2	2	6	-	-	-	-	25,602	2.36%	**1.0**
Montgomery Island	2	2	6	-	-	-	10	27,313	2.52%	**1.5**
New Cumberland	4	-	-	6	-	11	-	37,272	3.44%	**1.5**
Pike Island	4	-	-	6	-	9	-	43,643	4.03%	**2.0**
Hannibal	4	-	-	6	-	8	-	47,783	4.41%	**2.0**
Willow Island	4	-	-	6	-	8	-	45,802	4.23%	**2.0**
Belleville	4	-	-	6	-	8	-	48,641	4.49%	**2.0**
Racine	4	-	-	6	-	8	-	49,845	4.60%	**2.0**
Robert C. Byrd	4	-	-	6	8	-	-	56,079	5.18%	**2.0**
Greenup	4	-	-	6	-	9	-	68,695	6.34%	**2.5**
Meldahl	4	-	-	6	-	12	-	64,627	5.97%	**2.5**
Markland	4	-	-	6	-	12	-	60,011	5.54%	**2.5**
McAlpine	4	-	-	8	-	9	-	61,943	5.72%	**2.5**
Cannelton	4	-	-	6	-	12	-	64,257	5.93%	**2.5**
Newburgh	4	-	-	6	-	9	-	76,779	7.09%	**3.0**
Uniontown	4	-	-	6	-	10	-	85,718	7.92%	**3.0**
Smithland	4	-	-	8	-	11	-	93,337	8.62%	**3.0**
Olmsted	4	-	-	8	-	5	-	101,267	9.35%	**3.0**
Component Totals	**70**	**6**	**56**	**102**	**8**	**141**	**23**	**1,082,886**		
% of Total	**92%**	**8%**	**35%**	**65%**	**5%**	**82%**	**13%**			
System Cost Rank	**3.0**	**1.0**	**2.0**	**2.5**	**1.0**	**3.0**	**1.5**			
Sites w/ Compnt.	**100%**	**16%**	**16%**	**84%**	**5%**	**79%**	**11%**			
System # Rank	**3.0**	**1.5**	**1.5**	**3.0**	**1.0**	**3.0**	**1.0**			

System Cost Rank	
Overall %	Cost Rank
0 - 10%	1.0
11 - 25%	1.5
26 - 40%	2.0
41 - 65%	2.5
66 - 100%	3.0

System Number Rank	
Overall %	Number Rk.
0 - 15%	1.0
16 - 30%	1.5
31 - 45%	2.0
45 - 60%	2.5
61 - 100%	3.0

Consequence Ranking	
Site Overall %	Conseq. Rk.
0 - 2.5%	1.0
2.51 - 4.0%	1.5
4.01 - 5.5%	2.0
5.51 - 7.0%	2.5
Above 7.0%	3.0

Further Screening and Prioritization of Model Development

It was intended that reliability models would be developed for all 20 survivors for the ORMSS at the time of the screening. As model development progressed, a few changes to the original list of 20 survivors were made based upon judgment and schedule. For example, the reverse tainter gate culvert valve anchorage model was lumped into the overall reverse tainter valve model. Therefore, a single model covered both. Additionally, the butterfly valves were incorporated as part of the mechanical model for the lock since there was available data for the performance of butterfly valves relative to reliability analysis. Also, it was determined that a separate miter gate anchorage model was not necessary since previous analyses indicated the critical element to be the I-bars. Since the I-bars are switched out and maintained as part of normal maintenance, the component was eliminated from consideration. Also, there were two types of reverse tainter culvert valve models that had to be developed, one for horizontally-framed valves and the other for vertically-framed valves.

Additionally, the way the project was funded meant that only certain models could be initiated and completed in time for the interim report for J.T. Myers and Greenup. If all models were started, none would have been completed in time for this report. Therefore, the team agreed that the lock models were most critical since they potentially affected navigation delays, and thus, were a potential major factor affecting the economic analysis. The effort was initially focused on completing the reliability analysis for the lock components. Therefore, the dam models were not started until FY00 and will be included as part of the final ORMSS report. For the purposes of the economic analysis, dam rehabilitations were projected into the future based upon engineering judgment and historic field experience.

Screening Components Specific to J.T. Myers and Greenup

It was decided by the entire ORMSS team that the reliability results for lock components at J.T. Myers and Greenup were the most critical relative to the overall schedule and needed to be completed in time for the interim report. Therefore, the effort was focused on developing the necessary models and calibrating the runs in order to complete the analysis. The models listed shown in Table 6.1.1.C have been developed to date.

However, some of the other sites (projects other than J.T. Myers and Greenup) still need to have the runs calibrated and subjected to independent technical review for some models. The reliability results for all lock components at J.T. Myers and Greenup have been completed, calibrated and reviewed with the results incorporated in the overall economic analysis.

TABLE 6.1.1.B Original Phase 2 Screening Results

Type of Component	Engineering Discipline	System Number	Site Specific Consequence	Site Specific Cost	System Cost	System Consequence	Likelihood of Problems	Overall Ranking	Phase 2 Screening Results
Horiz. Framed Miter Gates	Structural	3.0	3.0	3.0	3.0	3.0	3.0	18.0	Reliability Analysis
Vert. Framed Miter Gates	Structural	1.5	3.0	3.0	1.0	1.5	3.0	13.0	Reliability Analysis
Lock Emergency Gates	Structural	2.0	2.0	3.0	1.0	1.0	2.0	11.0	Screened Out
Reverse Tainter Valves	Structural	3.0	3.0	2.0	2.5	3.0	3.0	16.5	Reliability Analysis
Butterfly Valves	Structural	1.5	2.0	3.0	2.0	1.5	3.0	13.0	Reliability Analysis
Dam Tainter Gates	Structural	3.0	3.0	3.0	3.0	3.0	3.0	18.0	Reliability Analysis
Vertical Lift Gates	Structural	1.0	3.0	3.0	1.5	1.5	3.0	13.0	Reliability Analysis
Roller Gates	Structural	1.0	3.0	3.0	1.0	2.0	3.0	13.0	Reliability Analysis
Boat-Operated Wicket Gates	Structural	1.0	1.0	1.0	1.0	3.0	1.0	8.0	Screened Out
Miter Gate Anchorage	Structural	3.0	3.0	2.0	1.0	3.0	2.0	14.0	Reliability Analysis
Tainter Gate Anchorage	Structural	3.0	2.0	2.0	1.0	3.0	2.0	13.0	Reliability Analysis
Vertical Lift Gate Anchorage	Structural	1.0	2.0	2.0	1.0	1.5	2.0	9.5	Screened Out
Roller Gate Anchorage	Structural	1.0	2.0	2.0	1.0	2.0	2.0	10.0	Screened Out
Reverse Tainter Anchorage	Structural	3.0	3.0	2.0	2.0	3.0	2.0	15.0	Reliability Analysis
Butterfly Valve Anchorage	Structural	1.5	2.0	2.0	1.0	1.5	2.0	10.0	Screened Out
Service Bridge Girders	Structural	3.0	2.0	2.0	2.0	1.0	1.0	11.0	Screened Out
Service Bridge Bearing Seats	Structural	3.0	1.0	1.0	1.0	1.0	2.0	9.0	Screened Out
Stilling Basins	Structural	3.0	2.0	2.0	1.0	1.0	2.0	11.0	Screened Out
Emergency Bulkheads	Structural	3.0	1.0	2.0	2.0	1.0	1.0	10.0	Screened Out
Culvert Bulkheads	Structural	3.0	1.0	2.0	1.0	1.0	1.0	9.0	Screened Out
Intake Screens	Structural	3.0	1.0	1.0	1.0	1.0	2.0	9.0	Screened Out
Miter/Quoin Blocks	Structural	3.0	1.0	1.0	1.0	1.0	2.0	9.0	Screened Out
Bulkhead Crane (Structural)	Structural	3.0	1.0	2.0	2.0	1.0	1.0	10.0	Screened Out
Maintenance Bulkheads	Structural	3.0	1.0	2.0	1.0	1.0	1.0	9.0	Screened Out
Tainter Gate Cable Anchorage	Structural	3.0	2.0	1.0	1.0	2.0	1.0	10.0	Screened Out
Service Bridge Bearing Memb.	Structural	3.0	1.0	1.0	1.0	1.0	1.0	8.0	Screened Out
Bulkhead Crane Lifting Beam	Structural	3.0	1.0	2.0	1.0	1.0	1.0	9.0	Screened Out
Poiree Dam	Structural	1.0	2.0	2.0	1.0	1.0	2.0	9.0	Screened Out
Floating Approach Walls	Structural	1.0	2.0	3.0	1.0	2.0	2.0	11.0	Screened Out
Chamber Monolith Stability	Structural	3.0	3.0	3.0	3.0	3.0	1.0	16.0	Reliability Analysis
Miter Gate Monolith Stability	Structural	3.0	3.0	3.0	3.0	3.0	1.0	16.0	Reliability Analysis
Concrete Horizontal Surfaces	Structural	3.0	1.0	3.0	2.0	1.0	2.0	12.0	Screened Out
Type of Component	Engineering Discipline	System Number	Site Specific Consequence	Site Specific Cost	System Cost	System Consequence	Likelihood of Problems	Overall Ranking	Phase 2 Screening Results
Guide/Guardwall Stability	Structural	3.0	2.0	3.0	3.0	2.0	2.0	15.0	Reliability Analysis
Fixed Weir Stability	Structural	2.0	3.0	3.0	2.0	3.0	2.0	15.0	Reliability Analysis
Sheet Pile Cellular Structures	Structural	3.0	2.0	3.0	3.0	2.0	2.0	15.0	Reliability Analysis
Pile Founded Structure Stability	Structural	2.0	1.0	3.0	2.0	1.0	1.0	10.0	Screened Out
Dam Pier Stability	Structural	3.0	3.0	3.0	3.0	3.0	1.0	16.0	Reliability Analysis
Mass Concrete	Structural	1.0	2.0	2.0	3.0	3.0	1.0	12.0	Screened Out
Overflow Spillway Stability	Structural	2.0	2.0	2.0	2.0	2.0	1.0	11.0	Screened Out
Miter Gate Sill Stability	Structural	3.0	3.0	2.0	2.0	3.0	1.0	14.0	Reliability Analysis
Dam Gate Sill Stability	Structural	3.0	3.0	2.0	2.0	3.0	1.0	14.0	Reliability Analysis
Retaining Wall Stability	Structural	1.0	1.0	2.0	1.0	1.0	1.0	7.0	Screened Out
Underseepage Control	Geotechnical	1.0	2.0	2.0	1.0	1.0	1.0	8.0	Screened Out
Erosion Control	Geotechnical	3.0	1.7	1.7	1.3	1.7	2.0	11.4	Screened Out
Slope Stability	Geotechnical	3.0	1.3	1.0	1.0	1.0	1.0	8.3	Screened Out
Riprap	Hydraulics	3.0	2.0	1.0	1.5	1.5	1.5	10.5	Screened Out
Navigation Channel Conditions	Hydraulics	3.0	2.0	1.3	2.0	2.3	2.0	12.6	Screened Out
Approach Conditions	Hydraulics	3.0	2.3	1.7	2.0	2.3	1.3	12.6	Screened Out
Dikes	Hydraulics	1.5	1.0	1.0	1.0	1.0	1.0	6.5	Screened Out
Tow Haulage Unit	Mech./Elec.	1.0	2.0	2.0	1.0	1.0	2.5	9.5	Screened Out
Bulkhead Crane Machinery	Mech./Elec.	2.7	1.3	2.3	2.0	1.0	2.3	11.6	Screened Out
Hydraulic Power System	Mech./Elec.	3.0	2.3	2.7	2.3	2.0	2.0	14.3	Reliability Analysis
Fire Protection Equipment	Mech./Elec.	1.3	1.0	1.3	1.0	1.0	1.3	6.9	Screened Out
Compressed Air System	Mech./Elec.	3.0	1.3	1.0	1.0	1.3	2.0	9.6	Screened Out
Lighting	Mech./Elec.	3.0	1.7	1.7	1.3	1.3	1.3	10.3	Screened Out
Emergency Generator	Mech./Elec.	3.0	2.3	1.3	1.0	1.7	2.3	11.6	Screened Out
Motor Control Center	Mech./Elec.	3.0	2.3	1.7	1.3	2.3	1.3	11.9	Screened Out
Power and Control Equipment	Mech./Elec.	3.0	2.3	1.7	1.7	2.3	2.0	13.0	Reliability Analysis
Dam Gages	Mech./Elec.	2.0	1.0	1.0	1.0	1.0	2.0	8.0	Screened Out
Intercom System	Mech./Elec.	3.0	1.0	1.0	1.0	1.0	1.0	8.0	Screened Out
Traffic Signal System/Lighting	Mech./Elec.	3.0	2.3	1.0	1.0	2.3	1.3	10.9	Screened Out

Total Number of Components Requiring Further Analysis --> 20

Table 6.1.1.C Status of Reliability Models at Time of Interim Report

Lock Component	J.T. Myers	Greenup	Other Applicable Ohio River Locks
Horizontally-framed Miter Gates	X	X	85%
Vertically-framed Miter Gates	n/a	n/a	100%
Horizontally-framed Culvert Valves	X	n/a	20%
Vertically-framed Culvert Valves	n/a	X	0%
Lock Electrical System	X	X	5%
Lock Mechanical System	X	X	5%
Unanchored Chamber Monolith Stability	X	X	60%
Anchored Chamber Monolith Stability	n/a	n/a	0%
Miter Gate Monolith Stability	X	X	85%
Guide/Guard Wall Stability	X	X	80%
Unanchored Miter Gate Sill Stability	X	X	100%
Anchored Miter Gate Sill Stability	n/a	n/a	0%

Notes: X indicates model is completed, runs are calibrated and is in economic analysis
n/a indicates component is not applicable to a particular project
% indicates model is completed with the percentage of other site-specific runs finished

No dam models have been developed to date, scheduled for FY00-01.

6.1.2 Types of Reliability Models

The reliability models developed for the components that listed in Table 6.1.1.B can be separated into two general categories: non-time dependent and time dependent models. The non-time dependent models are assumed not to deteriorate over time, whereas, the time dependent models are considered to degrade in reliability over time.

Time Dependent Reliability Models

Eight of the components shown in Table 6.1.1.B were considered time dependent. These components will degrade in reliability with time due to their cyclic use and associated age. The components considered time dependent are the miter gates (both horizontal and vertical), culvert valves (both horizontal and vertical), anchored lock wall stability, anchored miter gate sill stability, hydraulic power system, and power and control equipment. With the miter gates and culvert valves, these structures are steel structures that are subject to fatigue and corrosion, thus, causing a decrease in reliability over time. The fatigue of the miter gate and culvert valves is a function of the number of historical load cycles that the structure has undergone over time. For the mechanical and electrical components, the time reliability models are a function of the number of operating cycles, along with the component's age. For the anchored walls and sills, these structures are time dependent because the anchors are subjected to fatigue and corrosion. Hazard functions are developed for time dependent components. The hazard function is defined as the probability of unsatisfactory performance in a given year assuming it has survived up to that year.

Non-Time Dependent Reliability Models

The non-time dependent components were all the unanchored gravity structures: chamber monolith stability, miter gate monolith stability, guide/guard wall stability, and miter gate sill stability. The reliability of the gravity structures at the Ohio River projects has not deteriorated over time to the point that the stability of the structure is in question. Also, since the team is only looking at normal operating loads (normal and maintenance load cases), there is not an issue of return periods or extreme loads for cases such as earthquakes or excessive barge impact forces. Therefore, the models are assumed to have the same reliability over time. This is consistent with guidance, as provided by HQUSACE for gravity structures. For these components, the probability of unsatisfactory performance is computed and assumed to be the same for every year in study period.

6.1.3 ECONOMIC ANALYSIS FOR RELIABILITY MODELS

The annual probabilities of unsatisfactory performance for each component are only one of the inputs that the engineering team must supply to the economists for their analysis. The engineering team is also required to provide the economists with an event tree for each component depicting several repair options given the limit state of the component.

For all of the components for which reliability analysis was completed, the engineering team supplied probabilities of unsatisfactory performance for non-time dependent components and hazard rates for time dependent components. These values are provided for every year between 2000 and 2060. As noted previously for non-time dependent components, the values are the same in each year. However, for time dependent components, each year could have a different value.

The engineering team also provides event trees for each component to the economists. These event trees supply the economists with information regarding potential repair options if a component were to perform unsatisfactorily. Since the engineering team is only supplying probabilities associated with major types of unsatisfactory performance, the event tree reflects potential repairs for major events. Along with the repair scenarios, the engineering team also supplies the cost and chamber closure associated with each repair option, along with the effect the repair had on the component with regard to future reliability. Event trees vary for each individual component, however, the general format of each one is supplied in Figure 6.1.3.A. See the individual component sections for specific event trees.

FIGURE 6.1.3.A. Typical Event Tree for Reliability Models

Annual PUP	Level of Repair	Cost/Closure	Reliability Effect
	Repair Level 1 (%)	Repair 1 Cost and Chamber Closure Days	Repair 1 Effect On Reliability
Annual Probability Of Unsatisfactory Performance for Years 2000 – 2060	Repair Level 2 (%)	Repair 2 Cost and Chamber Closure Days	Repair 2 Effect On Reliability
	Repair Level 3 (%)	Repair 3 Cost and Chamber Closure Days	Repair 3 Effect On Reliability

The first branch of the event tree is the annual probability of unsatisfactory performance (PUP) for the component for any particular year between 2000 and 2060, the study period. The second branch is the level of repair associated with the annual PUP. In general this branch will have a two or three legs whose total percentage must equal 100 percent. The percentages were selected by the team of engineers that developed the model, in consultation with Operations personnel experienced with the repair techniques for the particular component. The third branch is the cost to repair the component for each level or repair, along with the amount of time in days the chamber is closed to navigation. These costs and closures again were developed by the engineering team that developed the model, along with consultation with appropriate Operations personnel. The last branch is the upgrade to future reliability based upon the repair. This effect is based upon engineering judgment on the team that developed the model.

6.2 HORIZONTALLY-FRAMED MITER GATE RELIABILITY

Each of the horizontally-framed miter gates on the Ohio River is of similar design and construction techniques. Each is designed for a 110-ft wide chamber and is constructed of built-up, welded members. The exception to this is the upper three auxiliary chamber miter gates for Emsworth, Dashileds, and Montgomery. These chambers are 56-ft wide and the gates are made from rolled members. Because these auxiliary miter gates at the upper three sites are not used very often, are relatively new from recent major rehabilitations, and they are constructed of rolled sections, it was decided by the team that a reliability analysis for these gates was not warranted.

6.2.1 Background

The horizontally-framed gates were separated into four distinct groups for their reliability analyses. The first group consisted of miter gates that had floating, welded pintle design with one set of diagonals per leaf. This group included the following sites: Willow Island, Belleville, Racine, Greenup, Meldahl, Markland, and McAlpine. The global finite element model for the first group was modeled after the Markland miter gates. The second group consisted of miter gates with fixed, bolted pintle design with two sets of diagonals per leaf. These sites included the miter gates at New Cumberland, Pike Island, and Hannibal. The second group global finite element model was based upon the downstream gates at New Cumberland. The third group consisted of miter gates with a fixed, bolted pintle design with one set of diagonals per leaf. These sites included Cannelton, Newburgh, J.T. Myers, Smithland, R.C. Byrd, and Olmsted. The basic, global finite element for group three was modeled based upon the Cannelton miter gates. The final group is the auxiliary chamber miter gates at Emsworth, Dashields, and Montgomery. As discussed previously, no reliability modeling was required for the group four miter gates. Refer to Figure 6.2.1.A for the grouping of Ohio River horizontally-framed miter gates.

The basis for the analysis and reliability model for all horizontally-framed miter gates on the Ohio River was based upon the Markland miter gates. Markland represents the oldest project on the Ohio River that has not been rehabilitated. The gates are experiencing fatigue cracking and are nearing the end of their original design life (assumed to be 50 years). The team originally investigated traditional strength and fatigue analysis associated with the main load carrying members for bending. After initial results indicated no potential problems at Markland for the entire study period, it was decided to refocus the effort towards actual field experience at Markland. It is important to note that other miter gates on the Ohio River have experienced similar cracking patterns, but to a much less extent than the current damage to Markland's gates. A brief history of the problems encountered with the Markland miter gates is described below followed by the development of the model and calibration.

Ohio River Main Stem Systems Study

Horizontally-Framed Miter Gate Information Sheet

Group	Site	Service Year	Lift (ft)	Pintle Design Base	Pintle Design Connection	Diagonals per Leaf	Number of Girders	Bottom Girder Depth	Web Thickness	Downstream Flange	Thrust Plate Thickness	x-dist. from quoin	Girder Depth at x-dist.	Flange Crack Length	Critical Crack Length	Upstream Flange
									Gate Properties at Pintle Area							
Group 1	Willow Island	1972	20	floating	welded	one	11	70"	5/8"	16 x 1	0.75" avg.	44"	38"	3.75"	23.31"	16 x 1
	Belleville	1965	22	floating	welded	one	12	70"	5/8"	16 x 1	0.75" avg.	44"	38"	3.75"	23.31"	14 x 1
	Racine	1967	22	floating	welded	one	13	70"	5/8"	18 x 1	0.875" avg.	44"	38"	4.25"	23.31"	20 x 7/8
	Greenup	1959	30	floating	welded	one	15	70"	5/8"	18 x 1	0.75" avg.	44"	38"	4.25"	23.31"	20 x 7/8
	Meldahl	1962	30	floating	welded	one	15	70"	5/8"	18 x 1	0.75" avg.	44"	38"	4.25"	23.31"	20 x 7/8
	Markland	1959	35	floating	welded	one	14	70"	5/8"	18 x 1	0.75" avg.	44"	40"	4.25"	23.31"	20 x 7/8
	McAlpine	1962	37	floating	welded	one	16	70"	5/8"	18 x 1	0.75" avg.	44"	40"	4.25"	23.31"	20 x 7/8
									Gate Properties at End of Quoin Diagonal Plate							
Group 2	N. Cumberland (u)	1959	20.5	fixed	bolted	double	8	61-3/8"	7/16"	15"x 5/8"	0"	100"	61-3/8"	7.28"	0"	15 x 1
	N. Cumberland (d)	1959	20.5	fixed	bolted	double	11	61-3/8"	3/8"	15"x 5/8"	0"	100"	61-3/8"	7.31"	0"	15 x 1
	Pike Island (u/s)	1963	21	fixed	bolted	double	9	61-3/8"	3/8"	15"x 3/4"	0"	100"	61-3/8"	7.31"	0"	15 x 1
	Pike Island (d/s)	1963	21	fixed	bolted	double	11	61-3/8"	7/16"	15"x 3/4"	0"	100"	61-3/8"	7.28"	0"	15 x 1
	Hannibal	1972	21	fixed	bolted	double	11	61-3/8"	3/8"	15"x 5/8"	0"	100"	61-3/8"	7.31"	0"	15 x 1
									Gate Properties at End of Quoin Diagonal Plate							
Group 3	Cannelton	1973	25	fixed	bolted	one	14	54"	1"	9 x 1	0"	89"	54"	19.3"	0"	18 x 2
	Newburgh	1974	16	fixed	bolted	one	12	54"	3/4"	9 x 1	0"	89"	54"	19.65"	0"	14 x1.25
	JT Myers	1972	18	fixed	bolted	one	13	54"	1"	9 x 1	0"	89"	54"	19.5"	0"	16 x 1.375
	Smithland	1979	22	fixed	bolted	one	13	54"	3/4"	9 x 1	0"	89"	54"	19.73"	0"	12 x 1
	RC Byrd	1993	23	fixed	bolted	one	12	70"	3/4"	12 x 1/2	0"	89"	70"	26.25"	0"	8 x 3/4
	Olmsted	2006	15	fixed	bolted	one	11	54"								
Grp 4	Emsworth Aux.	1982	18	fixed	bolted	one	15	24"	1/2"	7"x 7/8"						
	Dashields Aux.	1984	10	fixed	bolted	one	16	24"	1/2"	7"x 7/8"						
	Montgomery Aux.	1984	18	fixed	bolted	one	14	24"	1/2"	12-3/4"x 3/4"						

Figure 6.2.1.A. Ohio River Horizontally-Framed Miter Gate Data Sheet.

6.2.2 Overview of the Miter Gate Model

Serious concern regarding the integrity of the miter gates at Markland arose during a scheduled maintenance dewatering in 1994. This dewatering was scheduled to do major maintenance for the main chamber, including jacking the miter gates and replacing the pintle, seals, etc. However, once the chamber was dewatered and the gates were inspected, severe cracking at several locations was noted. Many of the cracks were at welded connections of the main load carrying members. In particular, the heaviest cracking occurred near the pintle area on the lower girders. It was determined that the extensive cracking was fatigue-related. Since the gates had seen less than 40 years of operation at the time of the 1994 dewatering, the fatigue of the gates was considered to be an abnormal failure mode. In order to determine the cause for this type of extensive cracking, the Louisville District hired an engineering consultant specializing in finite element modeling to help determine the cause for the early fatigue cracking. It was determined by LRL-ED and the consultant that the root cause of the early fatigue cracking was due to the original construction when the flanges and webs were welded together and subsequent repair methods when welding was used to repair smaller cracks throughout the history of operation. Because of the large number of structural members joining together in the pintle area, the entire region is highly constrained from movements due to temperature fluctuations. When welding occurs, large stresses are developed in the members near the weld joints. As the weld joint cools, large tensile stresses (termed residual stresses) are “locked” in place because the restraints of the gate in the pintle area. The large tensile stresses then are subjected to normal operating loads due to pool fluctuations as a chamber goes between upper and lower pool. When the gate is holding back pool, compressive stresses are applied to these areas where the tensile, residual stresses are locked in, thus, causing a stress reversal during each operation. This large reversal, coupled with the historical number of load cycles, has caused the fatigue-related cracking on these of gates. Figures 6.2.2.A through 6.2.2.E show several photos from the 1994 dewatering.

Figure 6.2.2.A depicts the widespread cracking present in the main chamber miter gates. The white arrows in the photo show areas where large cracks were found and in need of immediate repair. Note most of the cracking on this leaf is occurred where the vertical stiffeners were welded to the horizontal girders. Cracks initiated at that connection and grew through the girder flange.

Figure 6.2.2.B shows repair technique on one of the miter gate leafs. Repair consisted of gouging out the entire length of the weld and re-welding material back together. Note cracking on this leaf initiates at corners of small diagonal plates and girder/stiffener flanges and then proceeds through flange. Additionally, note extensive length of cracks.

Figure 6.2.2.C depicts cracking also prevalent near pintle region where diagonal plate is welded to the gate. White arrows show positions of extensive cracking. Note new flange for lower girder for this leaf. This was added due to damage to lower girder flange on this girder. This damage is shown in Figures 6.2.2.D and 6.2.2.E.

Figure 6.2.2.D shows main chamber miter gate damage to the lower girder downstream flange. Note damage to lower girder flange plate due to buckling of the web. The buckling of the web helped cause the connection between the web and flange plate to separate as shown in Figure 6.2.2.E.

Figure 6.2.2.E is a photograph that shows a close-up of the damage to the flange plate looking from "inside" the girder towards the downstream flange plate. Note the separation of the flange plate from the web of the girder.

Figure 6.2.2.A Main Chamber Miter Gate Cracking Above Pintle

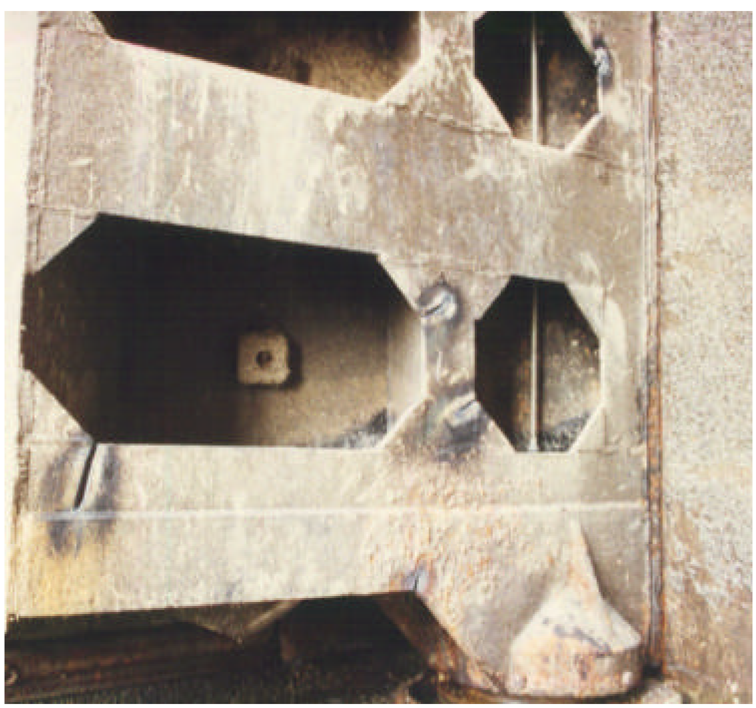

Figure 6.2.2.B Main Chamber Miter Gate Crack Repair in Pintle Region

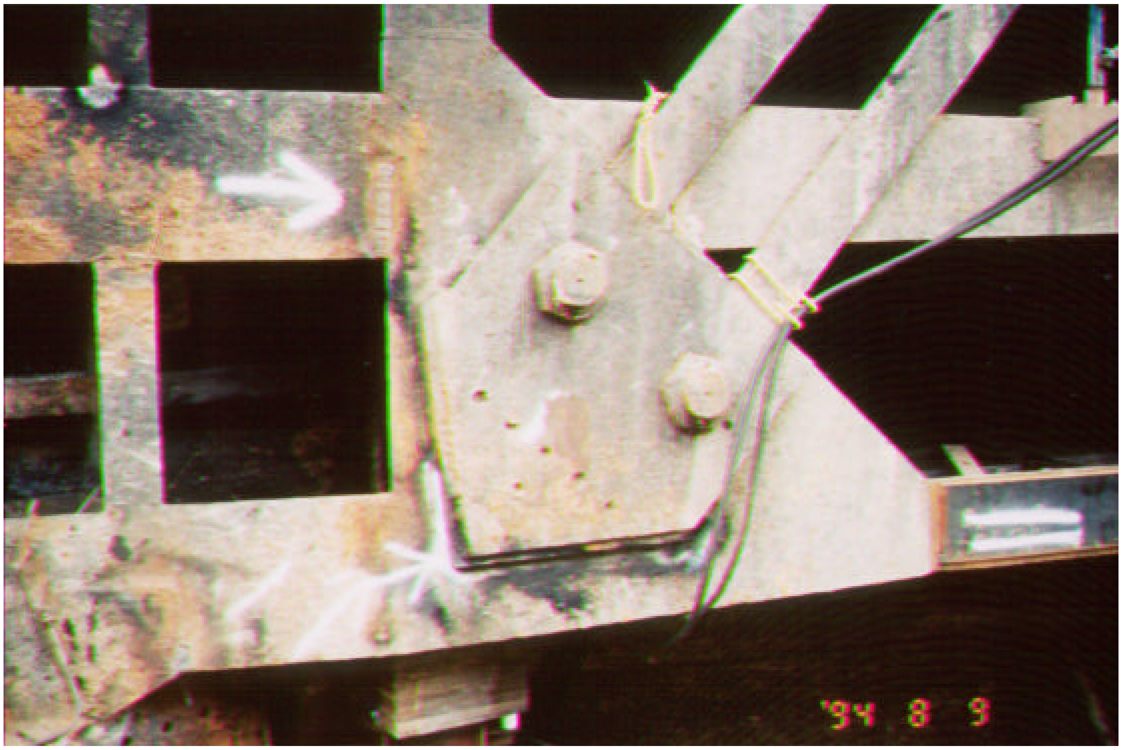

Figure 6.2.2.C Main Chamber Miter Gate Cracking Near Diagonal Plate

Figure 6.2.2.D Miter Gate Damage to Lower Girder Downstream Flange

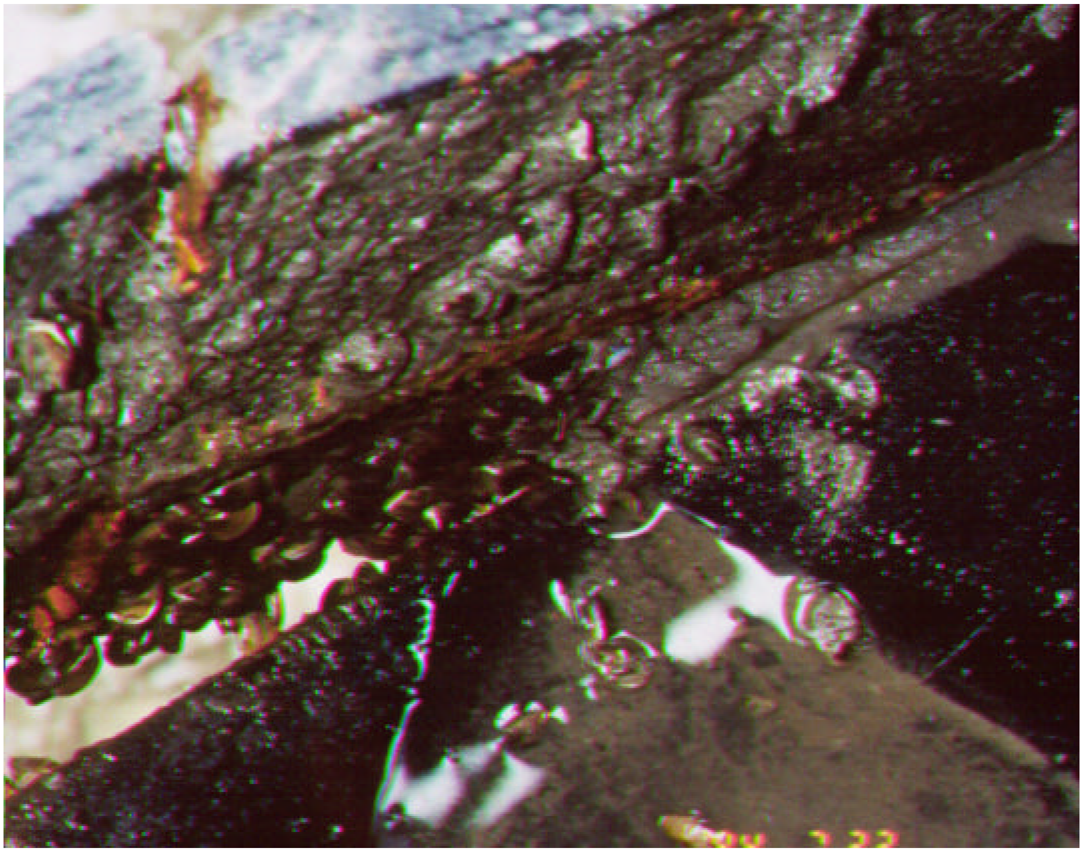

Figure 6.2.2.E Miter Gate Damage to Lower Girder Downstream Flange

6.2.3 Finite Element Modeling of Miter Gates and Calibration

The fatigue cracking problem at welded flange connections on the Markland miter gates was summarized in previous sections. To evaluate the fatigue cracking problem from a reliability standpoint, the initiation and growth of the fatigue cracks must be characterized in terms of the variability of the parameters that control the fatigue cracking. The development of such a reliability model has three major components; 1) to determine the characteristics and variability of the initiation of fatigue cracks, 2) to establish the rate of crack growth and its variability, and 3) determine the limit state of the gate, which is defined as the extent of fatigue crack growth that will compromise the integrity of the gate. The determination of the limit state of the miter gate is described in the next section.

The fatigue crack initiation and growth is primarily influenced by the residual stresses that develop during the welding of the girder flange and vertical stiffener flange. Large tensile residual stresses can develop in the flanges around the welded area due to constraints against thermal expansion (and contraction) during the welding process. The arch action of the gate under hydrostatic operating loads develops compressive stress in the flanges in the pintle region. These compressive operating loads, which are exasperated by the geometric re-entrant corner at the welded flange connection and the usually rough surface at the weld bead, produce large stress cycles that initiate fatigue cracks.

A numerical study using finite element modeling was conducted to evaluate the cracking at welded flange connections.[1] As depicted in Figure 6.2.3.A, this study used global modeling of the gate leaf to define the range of compressive loads that develop in the girder flanges near the welded connections. Normal operating conditions as well as pintle wear and gate misalignment were considered. Detailed local models of the flange connection were used to establish the residual stress distributions by numerically simulating the weld process. This methodology was benchmarked against test data from the literature where stress magnitudes and distributions were measured around a weld on A36 steel as illustrated in Figure 6.2.3.B. Once the residual stress field was established in the local model, the flange loads were applied consistent with the global operational loads. The stress range for a cycle of operation was determined from a gate open condition, which includes gravity load, diagonal prestress, and residual stresses, to a gate closed condition that adds the operational loads. This stress range is then used to evaluate the number of cycles for crack initiation based on the American Society of Mechanical Engineers' design fatigue curve for carbon steel.[2] This calculation for fatigue crack initiation correlated very well with the observed cracking in the Markland miter gates during the 1994 and 1996 dewatering inspections.

The next step was to develop a method for evaluating the rate of fatigue crack growth. Typically, the linear elastic fracture mechanics (LEFM) based formulas for stress intensity as a function of stress level and crack length of the form,

$$K = Q\sigma\sqrt{\Pi a}$$

are used to develop a relationship for the change in stress intensity versus crack length. This stress intensity relationship is then used with the Paris relation,

$$da/dN = C(\triangle K)^{n}$$

Where C and n are material parameters (with variability) for integration to find the crack growth rate. This method is illustrated in the Corps of Engineers' procedure for structural inspection and evaluation of welded lock gates.[3] However, these LEFM formulas are developed based on uniform far field stresses and, most often, Mode I crack growth. In this case, the driving stress for crack growth is the tensile residual stress distribution at the crack rather than the remote compressive flange stress. Moreover, these residual stresses change as the crack extends. Thus, another method for determining the rate of crack growth was required. The method that was developed in the Markland study was to extend a crack within the residual stress field in the local finite element model and compute the resulting stress intensity value under gate open and closed conditions. This was accomplished using the J-integral method to calculate the energy release rate for an increment of crack extension. The stress intensity value is computed from the energy release rate using LEFM assumptions. This energy based method also accounts for contributions to crack growth from all modes of crack extension. The Mode II or shear contribution is considered significant in this situation. Thus, a relation for stress intensity versus crack length was constructed by numerically extending a crack from the corner of the welded flange connection in the local model for gate open and closed conditions. The range of stress intensity versus crack length was then used to integrate the Paris relation to determine the crack growth rate of the fatigue cracks. As illustrated in Figure 6.2.3.C, this calculated crack growth rate correlated very well with the observed crack lengths in the Markland gates during the 1994 and 1996 dewaterings.

The development of the reliability model for horizontally-framed miter gates is based upon the above methodology. The intent of the model is to characterize the variability of the fatigue crack initiation and growth. The engineering team evaluated the importance of the parameters that influence fatigue cracking to establish the variables for characterization. A matrix of calculations is then performed with variations of these variables to develop relationships on the fatigue crack initiation and growth. The residual stress at a welded connection is influenced by many parameters, such as type of weld, number of passes, yield strength, strain hardening characteristics of the base metal and weld metal, and the degree of

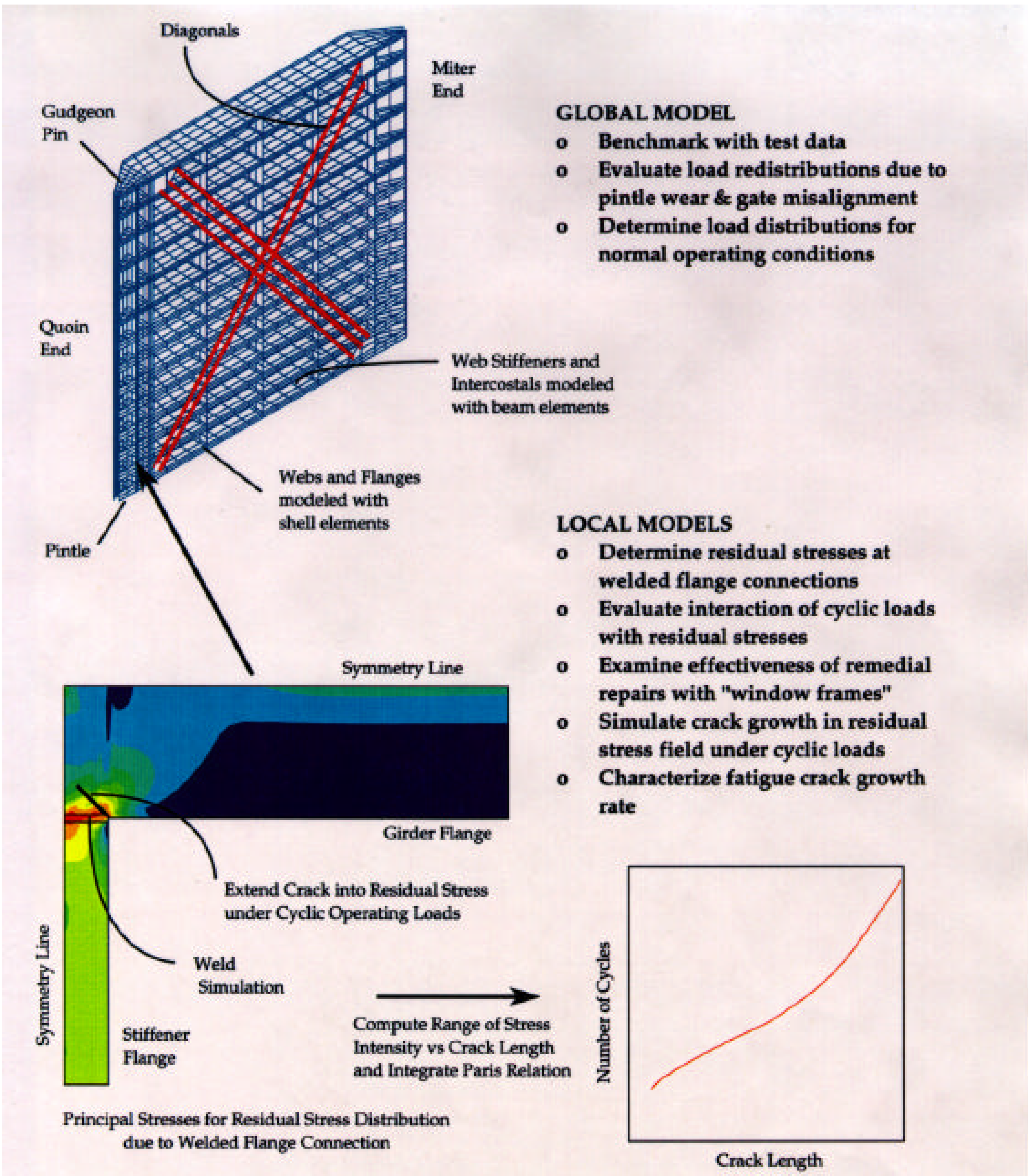

Figure 6.2.3.A Global Finite Element Model of Markland Miter Gates

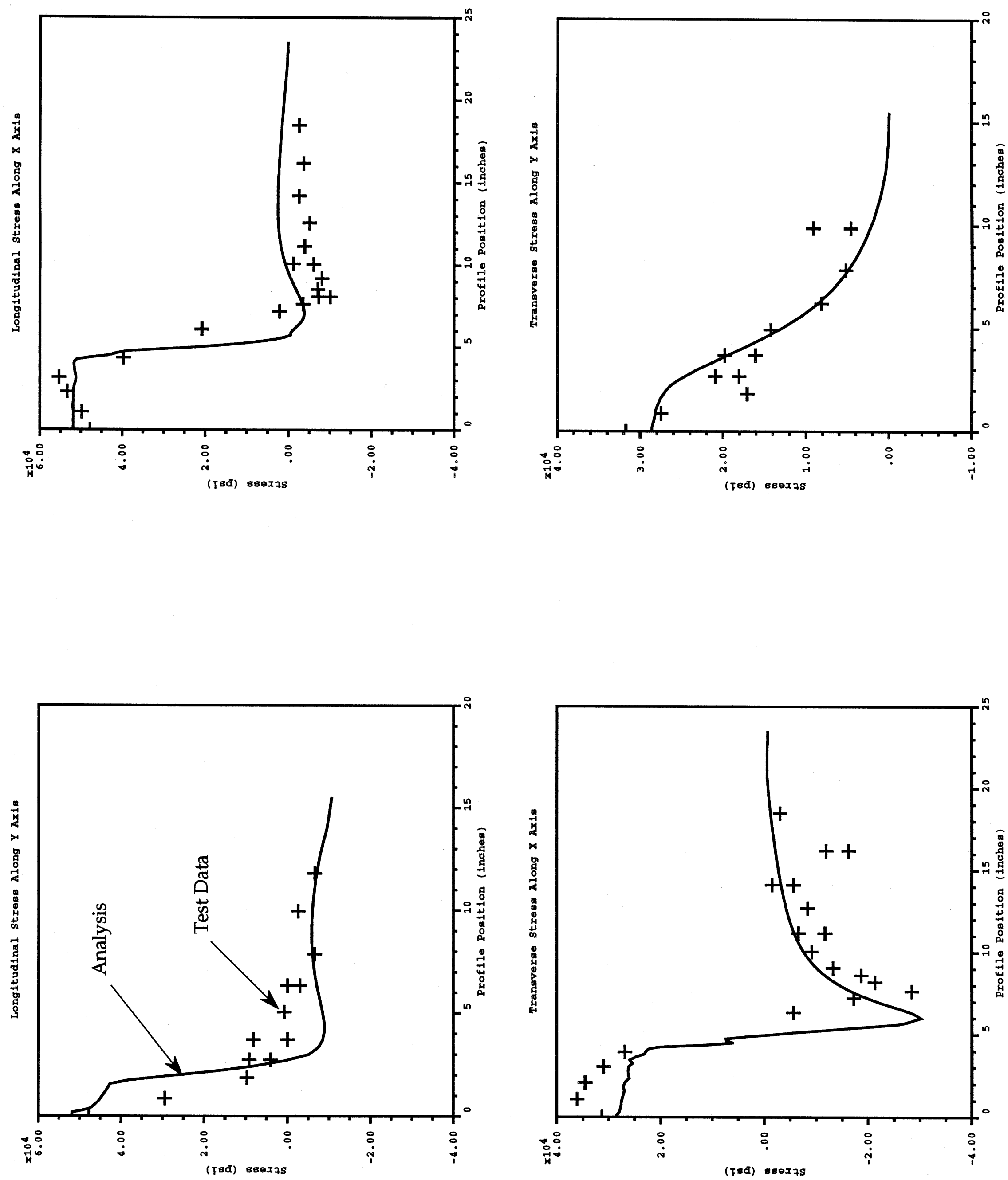

Figure 6.2.3.B Stress Distribution Around Welds on A36 Steel.

Constraint during welding. The Markland miter gates demonstrated that modeling the weld process was not necessary to develop a reasonable residual stress distribution around the welded areas that govern the extended growth of fatigue cracks. Based on this work, the engineering team identified the material yield stress and the degree of constraint as the important random variables for developing the residual stress distribution at a welded connection. The temperature dependence and strain hardening variations are tied to the variation in yield stress. The degree of constraint is incorporated in the evaluation by considering three different types of welded connections. Thus, local models are developed for 1) the stiffener flange to girder flange connection, 2) the pintle casting to lower girder connection, and 3) the diagonal anchor plate to girder flange connection. These connections represented areas of the miter gate where fatigue cracking has been observed and are considered likely to have serious reliability consequences for extended cracking.

The fatigue cracking is also governed by the compressive side of the stress cycle, so that the reliability model must be characterized in terms of operating stress on the connection, typically the girder flange stress, which can be related to the head variations. Finally, the crack growth is defined by the material constants in the Paris relation, and the material coefficient is also defined as a random variable. Thus, for each local connection model, analyses are conducted with material variation in yield stress to develop the resulting variations in residual stress distributions. Then variations of flange stress are applied to each variation of residual stress to develop combinations of stress ranges. That is, curves of peak tensile residual stress versus yield stress are constructed along with curves of peak compressive stress acting on the residual stress field vs. nominal flange stress. These relations are then fit with equations for defining the reliability model. The variation in crack initiation is characterized by evaluating the variation in cyclic stress range for given values of the random variables and using the ASME fatigue design curve to define the allowable number of cycles for crack initiation. A variation on the fatigue design curve was not considered necessary since this curve has been adjusted for material variation and because the results using the above method benchmarked very well with the observed crack initiation on the Markland gate.

The variability of the fatigue crack growth is developed in a similar manner. Cracks are extended in the variations of residual stress distributions for different variations of operating flange stresses to develop families of curves for stress intensity versus crack length. These variations are then used to integrate the Paris equation with variations in the material constant to develop families of curves for crack length vs. number of cycles for the variations in yield stress, flange stress, and fatigue rate coefficient. An equation is then fit to this data and the incremental form used to return an increment in crack extension for a given number of cycles and current values of the random variables.

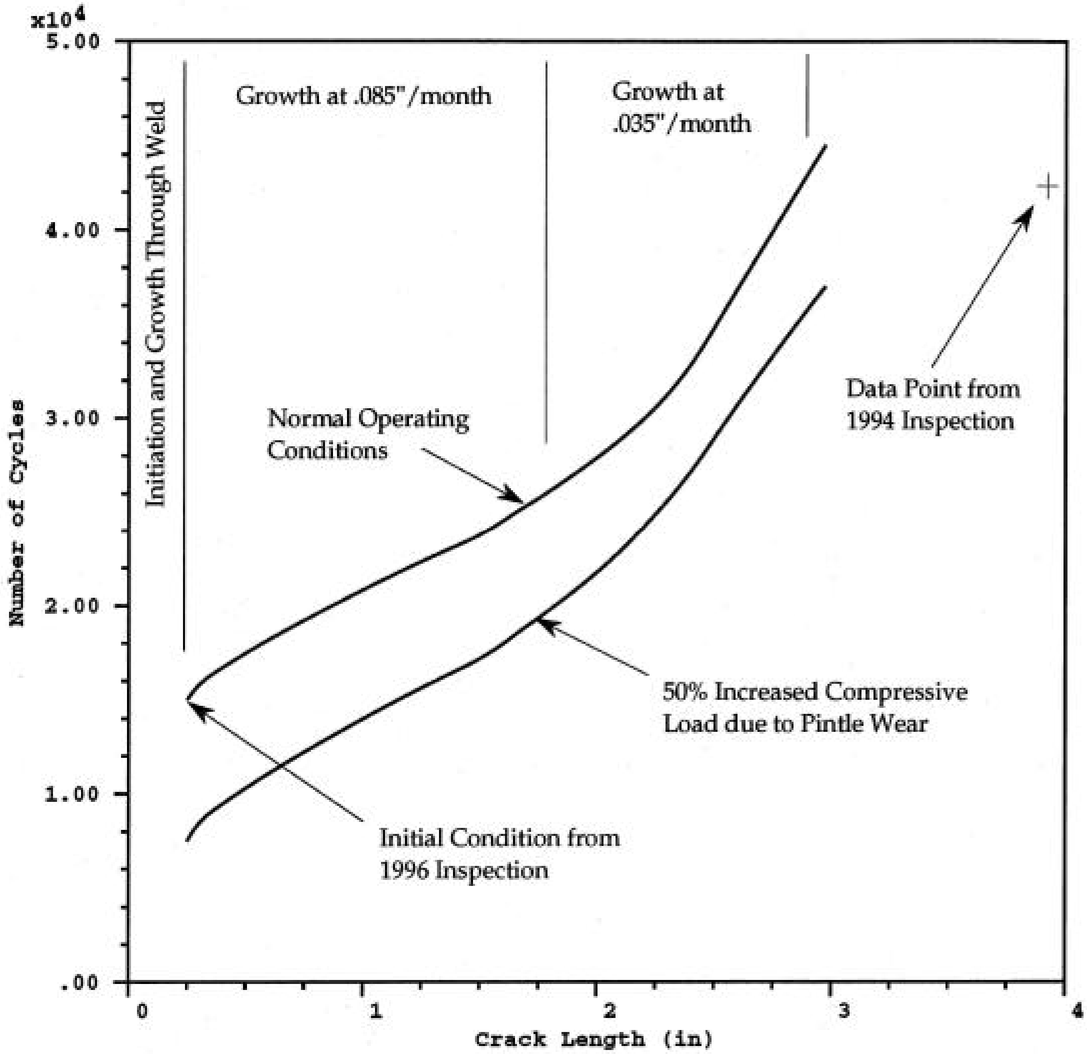

Figure 6.2.3.C Graph Depicting Crack Growth Rate Versus Operating Cycles

6.2.4 Limit State of the Miter Gates

The methods and procedures used to characterize the initiation and growth of fatigue cracks at welded connections was described in the previous section. The next component in the reliability model is to define the limit state of the gate, which is the extent of fatigue cracking that will compromise the integrity of the gate. As the fatigue cracks grow into the flanges, the effective area for compression loads is reduced, and the effectiveness of the flange in preventing buckling of the webs is reduced. In the quoin region where compressive loads are high, buckling of the girder webs could lead to progressive failure of the gate. The limit state of the gate is thus defined by considering the degradation on the buckling characteristics for the growth of fatigue cracks. A baseline for the margin against buckling under normal operating loads is first established for the undamaged gate. Fatigue cracks are then extended in the global model by disconnecting elements in the mesh. Buckling calculations are conducted for increasing levels of damage until a criteria defining the limit state is reached.

For these redundant structures, local buckling can be tolerated without seriously compromising the gate integrity. Local buckling of girder webs in diaphragm bays is known to occur without serious consequences. In the buckling calculations, an eigenmode method is used to find a factor (eigenvalue) on the operating loads such that the associated buckling shape (eigenvector) has a zero stiffness. A sequence of buckling shapes and associated load factors is determined. A criteria must be established for the buckling characteristics that define a limit state for the gate. The criteria defined for this study is that any of the following conditions warrants a limit state that compromises the integrity of the gate;

(1) A buckling mode that extends over more than 1 girder (global buckling),
(2) A buckling mode that extends over more than ½ of a girder,
(3) Whenever the lowest buckling mode has a load factor less than 1.1.

Since the buckling characteristics are highly dependent on initial imperfections and the buckling calculations consider only nominal (perfect) geometries, the last criteria for a 10% safety factor is deemed appropriate. The buckling calculations also do not consider the progressive nature of buckling in that each calculated buckling mode is independent of the previous modes occurring with smaller load factors.

For each type of connection, the limit states are determined by progressively incorporating fatigue cracking damage into the global model and evaluating the buckling characteristics against the above criteria. Table 6.2.4.A summarizes the levels of damage found to constitute limit states for the gate under fatigue cracking damage. The level of damage needed for failure due to cracking at the pintle casting connection and for the diagonal anchor plate to girder flange connection were found to be much greater than for the stiffener flange to girder flange connection in the pintle region. In addition, the crack initiation phase is typically longer and the growth rate slower due to lower compressive working stresses at these connections. The residual stresses are also lower because there is usually less constraint at these connections during the welding of the connection. Therefore, it was found and concluded by the engineering team that the stiffener flange to girder flange connection is the controlling case for reliability of the miter gates for Group 1. It was determined that the cracking at the girder flange to the diagonal anchor plate was the controlling case for the Group 3 miter gates, which includes J.T. Myers. Figure 6.2.4.A illustrates the buckling mode for the undamaged Markland gate. Figure 6.2.4.B illustrates the level of damage needed to compromise the integrity of the gate due to buckling of the girder webs in quoin region. This level of damage basically needs to be such that the horizontal flanges are rendered completely ineffective in supporting the webs on the bottom two girders.

The first scenario investigated was that the cracks initiating in the girder flange at the corner of the connection would grow through the flange width to reach the web. Cracking would need to initiate and proceed from both the top and bottom of the flange and at the connections on both ends of the span along the web between stiffeners. However, as this type cracking develops, the global model showed that the resulting load redistribution in the gate would inhibit the continued crack growth at two of the opposite corners of the flange connections. The detailed local models also indicated that while the crack starts along a 45° angle from the corner of the connection, the residual stress field would cause the crack to turn horizontal toward the stiffener web. This leads to the conclusion that the fatigue crack would turn and grow into the secondary residual stress field of the welded connection joining the stiffener web on the underside of the girder flange. Because of the continuous tensile residual stress along the flange to girder connection, the fatigue crack is likely to have a fairly constant growth rate during this mode for very long crack lengths. As the cracking extends toward the girder web along the stiffener to girder flange connection, the large compressive loads in the girder will then cause the cracking to continue along the girder web to girder flange connection. This type of cracking at the girder web to girder flange connection has been observed in the Markland gate in the diaphragm bay next to the quoin region. This cracking will completely separate the flange from the web leading to buckling of the web in the highly compressive load region. Because the local models of the welded flange connection only considered the growth of the fatigue crack in the girder flange, an additional local model was developed to define the growth rate of the crack along the flange to web connection. This model required three-dimensional finite element modeling because of the geometry involved.

Table 6.2.4.A Levels of Damage for Limit State of Markland Miter Gate

Type of Connection	Level of Damage Required for Gate Instability
Girder Flange to Stiffener Flange in Quoin Region	Separation of Girder Flange on Bottom 2 girders
Girder Flange to Diagonal Anchor Plates at Quoin Region	Cracking through Flanges and into girder web for 1/8 of web depth on bottom 2 girders
Welded Pintle to Bottom Girder	Extensive Cracking Required. Will not Govern Fatigue Life

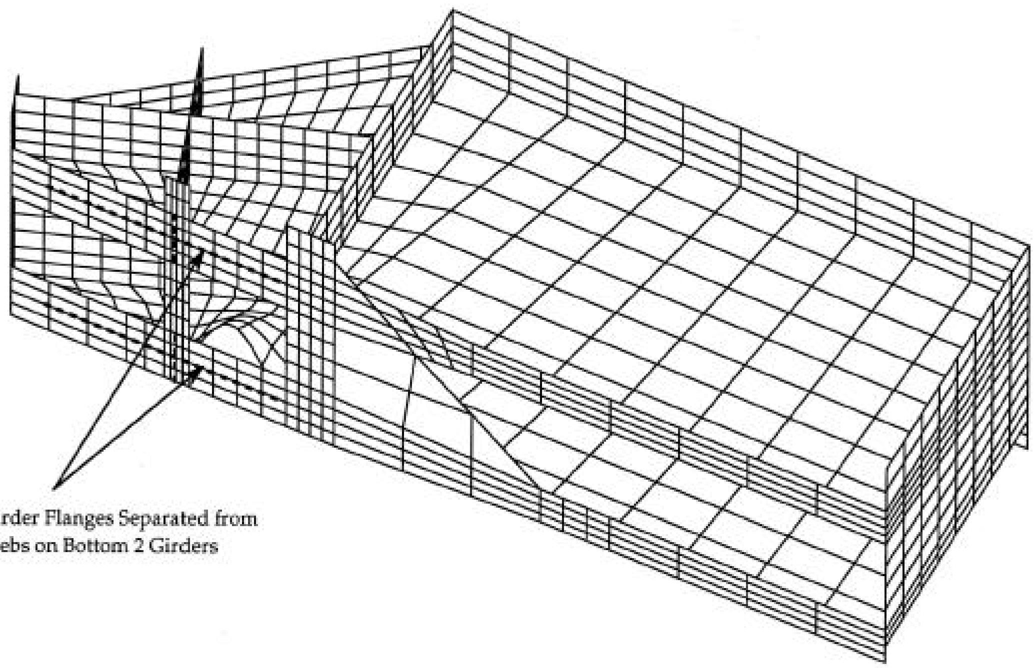

Figure 6.2.4.A Buckling Damage of Markland Gate from Finite Element Model

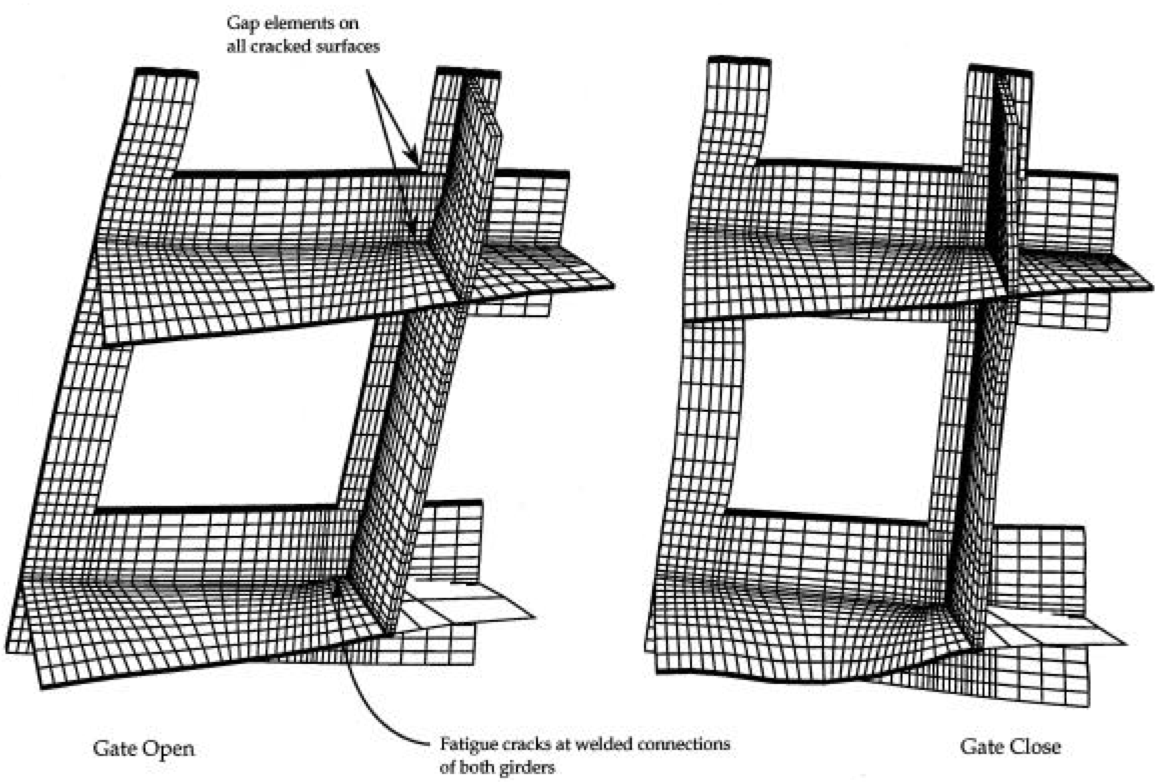

Figure 6.2.4.B Buckling Damage Required for Major Failure of the Miter Gates

6.2.5 Baseline Condition for Horizontally-Framed Miter Gates

The baseline condition represents the current Louisville District Operations personnel's method of operation concerning Ohio River lock maintenance. In general, the main chambers are dewatered at 5-year intervals for inspection and routine maintenance on the entire chamber. These dewaterings are usually 10 to 15 days in duration and repair work consists of inspection of the miter gate, along with minor repairs. Additionally, an overall inspection of the chamber is completed including machinery and valves. However, every 15 years (or the third dewatering of the 5-year cycle) is for significantly more maintenance to the chamber. At this dewatering, the miter gates are jacked in place and pintles, seals, and quoin/miter blocks are re-worked or replaced. Other chamber work also takes place during this dewatering such as culvert valve repair, gate and valve machinery work, along with clearing the culvert of debris build-up. These larger dewaterings usually take anywhere from 30 to 45 days.

Because the work involved with the normal maintenance schedule is generally for repair/replacement of maintenance items (seals, pintles, etc.), it is assumed that normal maintenance does not upgrade the overall reliability of the gate from a fatigue and corrosion standpoint. Therefore, for the reliability assessment, the baseline condition is considered a "fix-as-fails" approach.

6.2.6 Reliability Model Parameters

The reliability analysis for the horizontally-framed miter gates was developed to focus specifically on the type of cracking and problems that were occurring in the field. In order to accomplish this effort, the team focused its effort toward developing a model based upon the finite element analysis of the Markland miter gates. It was learned from developing the vertically-framed miter gate model for ORMSS that using the spread sheet on time dependent models was time consuming and often difficult to track changes and output. After initially developing a basic model with the spreadsheet, the engineering team decided to develop a Visual Basic coded model specifically for the ORMSS horizontally-framed miter gates and use Markland as the basis for the analysis. Therefore, the team coded their own model focusing on the cracking of the miter gates near the pintle and used @Risk™ libraries for the Monte Carlo simulation within the reliability model. Immediately, it was determined that the coded model served the team's needs better for this component as it was easier to track changes and make calibration runs. The model was named HWELD since it was based upon the premise of crack initiation at welded connections.

6.2.7 HWELD Reliability Model Input

The following sections detail the input menus for HWELD for running a reliability analysis for a set of ORMSS horizontally-framed miter gates. A few of the sections have figures supplied with them for the Markland input values to give the reviewer a feel for inputting data into the program.

A) Lock Information. The first portion of input file is the project location, chamber, and girder that is being analyzed. For most ORMSS sites, the miter gates for both the main and auxiliary chamber gates are the same in terms of design and construction technique. However, operating cycles and age are different for the chambers and thus, each must be analyzed separately. The input menu from HWELD for the Markland miter gates is shown in Figure 6.2.7.A as an example.

B) Cross-Section Properties of Miter Gate. The properties of the miter gate girder are required in order to compute the operating stresses in the area where the gate is susceptible to cracking. The required input for cross-section properties of the miter gate in HWELD is for the web/flanges, thrust plate, and overall gate geometry. The values are treated initially as constants but decrease over time in thickness dependent upon the paint life and corrosion rate. A series of input menus guide the user through the necessary property inputs for the girder properties, thrust plate properties, and finally, the overall gate geometry.

Web/Flanges – The inputs required for the upstream (u/s) and the downstream (d/s) web/flanges in HWELD are the thickness and width of the flange and the thickness and depth for the web in the quoin area. The x-distance is defined as the "section cut" from the quoin contact block to the critical point of interest where cracking of the welded connection is being considered. Since cracking for the base case (Markland) miter gates is widespread in the pintle region, the average x-distance is used for the middle diaphragm location. As an example, the HWELD web/flange property input values for the web/flanges cross-section properties for Markland are shown in Figure 6.2.7.B.

Thrust Plate – The HWELD inputs for the thrust plate are the width, thickness, and the distance from the downstream (d/s) flange.

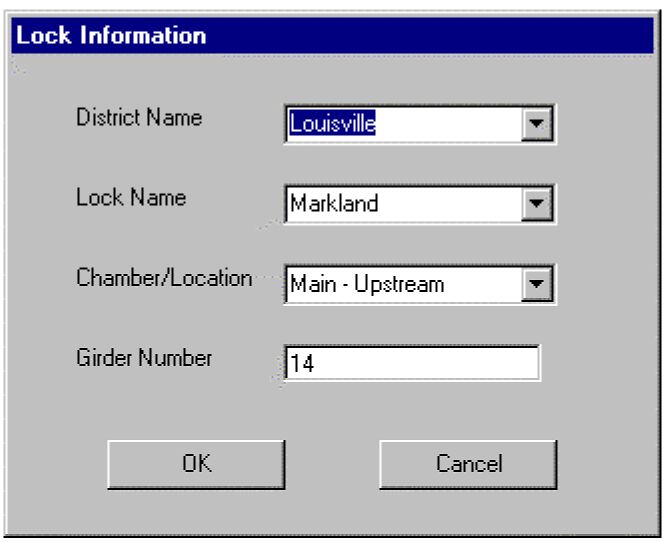

Figure 6.2.7.A Lock Information Input Menu for HWELD Reliability Model

Geometry – The required inputs for the geometry of the horizontally-framed miter gate are the gate height, spacing of girders, skin plate thickness, and working length. Other data is input into HWELD and is not directly used in the reliability calculations. This data is used only for information and includes items such as the gate height, length of girders, and tangent of angle that the girders are oriented.

<u>C) Crack Parameters</u>. The crack parameters required for the HWELD program are the initital crack length, the flange crack length, and the critical crack length. The initial crack length is set to a default value of 0.25 inches. This value is based on the results from the finite element analysis discussed in the previous section. The flange crack length is the distance from the initial crack through the flange to the web. The critical crack length is defined as the critical distance along the web and flange welds to which the limit state buckling of the thrust plate occurs.

D) <u>Head Histogram</u>. The head histogram reflects the actual past distribution of head differential for operating cycles for the each set of miter gates. This distribution is based on true daily lockage cycles available from the Lock Performance Monitoring System (LPMS) combined with the true head differential for each day. This distribution is valuable in determining the fraction of annual cycles versus the expected head differential that is used for fatigue analysis. The head histograms developed by WES are based on data collected and analyzed for approximately 12 years (1984–1995, inclusive) of lock operation. The HWELD program allows the input of up to 20 different blocks for head (at specified midpoints for ranges) and fraction of cycles from the histograms. This histogram is used in HWELD to parse the input annual cycles into the defined stress range blocks and number cycles for fatigue analysis. The example head histogram input for Markland is shown in Figure 6.2.7.C.

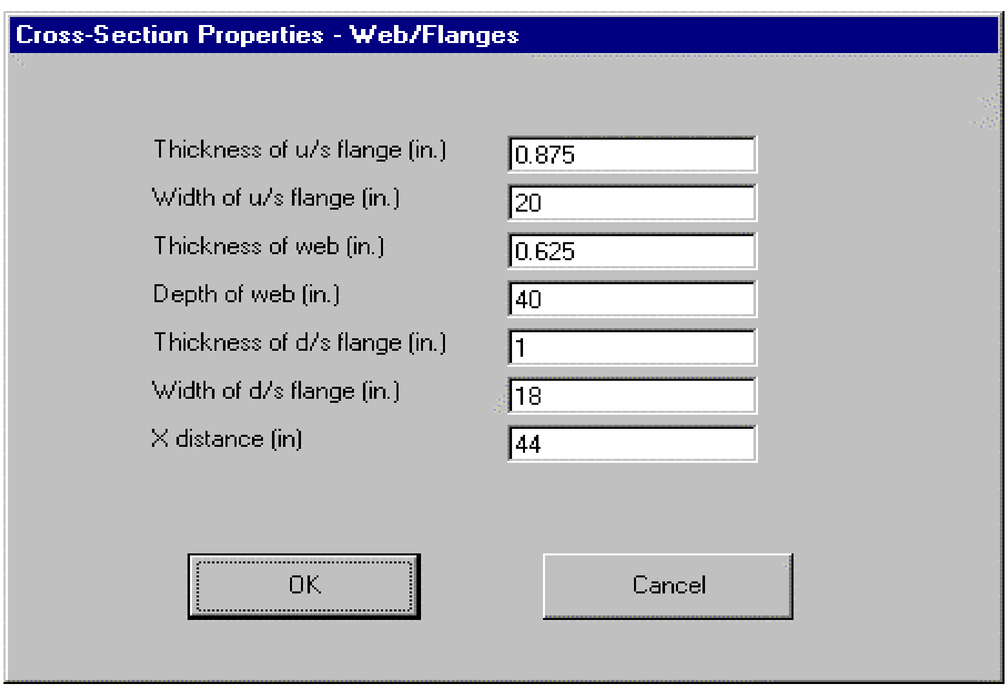

Figure 6.2.7.B HWELD Web/Flange Properties Input Menu

E) Traffic Cycles. The number of operating cycles for the gates are determined for each lock based on actual and predicted future cycles for the study period. The cycle information is used in fatigue analysis incorporated into the HWELD program. The cycles are input from the start of operation to the end of the study period. Operating cycles from the origination of the each project through 1983 were determined by going through the log books to determine the number of lockages in each chamber. From the LPMS data from 1984 through 1995, a ratio of lockages to operating cycles was determined and assumed to be the same in the past as well as for future projected cycles. Traffic cycles for 1984 through 1995 was determined using LPMS data. Finally, projected traffic through the end of the study period was determined by LRH's Navigation Center in Huntington, WV.

F) Paint History. The painting of the miter gates can be incorporated in the reliability analysis. This directly effects the corrosion of the gate members based on the defined paint life. The input required is the specified paint life and the year in which the gates were painted. These paintings are assumed to be for the entire gate and not just spot painting of gate. If a gate is painted after the initial paint life is exceeded then corrosion is not invoked until the end of the paint life. Paint histories can be entered for up to three different years.

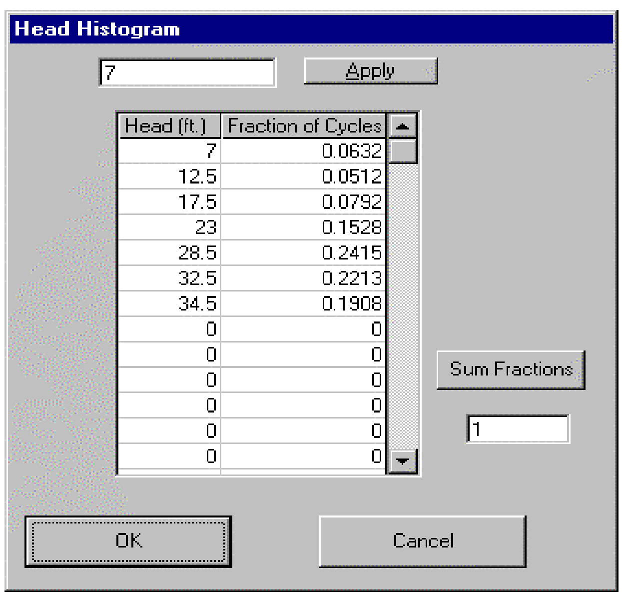

Figure 6.2.7.C HWELD Head Histogram Input Menu

6.2.8 Random Variables

The random variables incorporated into the reliability analysis of the miter gates are the yield strength of the steel, corrosion rate, stress concentration factors, and misalignment/pintle wear factors. These random variables are simulated using either direct Monte Carlo simulation or a modified simulation method called Latin Hypercube. The Latin Hypercube method utilizes stratified sampling of the input distributions for quicker convergence and both methods are incorporated into the HWELD program. Pool level differential between the upper and lower pools (commonly referred to the head) is essentially a random variable because the actual histogram allows for heads in eight different ranges but the values are not chosen separately for each iteration, therefore, it represents a truer measure of the pool level distribution at each project. The input distributions and statistical moments for the random variables are defined in the sections below.

A) Yield Strength. The distribution for yield strength is based on data from the published literature and previous Corps of Engineers reliability studies. The distribution is based on a truncated lognormal with a nominal yield stress of 38.88 ksi (i.e., mean yield strength times the strength ratio) and a standard deviation of 5.44. The lower limit for truncation is based on one standard deviation below the nominal (33.88 ksi) and the upper limit is based on approximately two standard deviations above the nominal (51 ksi).

B) Corrosion Rate. The distribution for corrosion rate is based on the data from the published literature and previous Corps of Engineers reliability studies. Corrosion is based on a power law that has been fit to actual field data in various corrosive environments. The equation used for the corrosion is $C(t) = A*t^B$, where A is a random variable based on field measurements, B is generally a constant based on different corrosive environments and C(t) is the corrosion in micromils/yr.[4] For this report, the mean value of A was selected based on submerged corrosion since the portion of the gate that was being investigated is always below lower pool. This distribution used for A was a truncated lognormal with a mean value of 77.33 and standard deviation of 24. The upper limit of the distribution was taken at 128 and the lower limit at 32. The value for B was a constant of 0.593. These limits and constants are based on actual field measurement of submerged hydraulic steel structures.

C) Stress Concentration and Pintle Misalignment/Wear Factors. Two types of factors are utilized in the reliability model to account for differences in stress values between traditional hand calculations and finite element analysis. One adjustment is the stress concentration factor due to the intensification of the stress in the flanges near the pintle area. Separate local finite element models specific to each miter gate group were run to determine group-specific stress concentration factors, thus, not all sites used the same values for input. Additionally, a gate misalignment and pintle wear factor that accounts for an increase in stress in the girder flange during operation is provided in the analysis. The adjustment values for both the stress concentration and misalignment/pintle wear factors were based upon finite element modeling results and calibration with field test data at Markland. The distribution for the stress concentration factors was considered uniform, meaning that any number within the specified range has equal chance of being selected in an iteration, since only the upper and lower limits can be well defined as well as the equal for the probabilities. For Group 1 (Greenup, Markland, etc.), the minimum stress concentration factor value was determined to be 1.1 and the maximum value to be 1.4. For Group 2 (Cannelton, etc.), the minimum value was determined to be 1.2 with a maximum of 1.8. For Group 3 (J.T. Myers, etc.), the minimum stress concentration factor value was determined to be 1.4 and the maximum value to be 2. The misalignment and pintle wear factors were determined on a percentage increase in the flange stress. A truncated lognormal distribution was selected with a mean of 20% with a standard deviation of 30%. The lower limit was 10% and the upper limit taken as 50%. Again, these values were calibrated with the field measurements relating to cracking at Markland and were assumed to be the same for all groups.

6.2.9 HWELD Reliability Model for Horizontally-Framed Miter Gates

A) Reliability Model Purpose. The computer program HWELD has been developed to complete a reliability analysis of the horizontally-framed miter gates for Ohio River lock projects. The model is used to determine if it is a better decision to replace the gates at some scheduled date as opposed to fixing them after they perform unsatisfactorily.

B) Reliability Analysis. The basis of the model is that it is a time dependent reliability model for a structure subject to fatigue and corrosion. Therefore, input items such as paint history, corrosion rates, and other variables are used in conjunction with the operating cycles to determine the time dependent reliability of the structure. Using the analysis and limit state information from the finite element modeling, HWELD computes the time dependent reliability of the miter gates given the input values. For each iteration, the model determines the year in which a fatigue-related crack initiates and marks that year. Once the crack reaches the first length, the crack is allowed to grow relative to the operating cycles within the histogram for each year after the time which it initiates. The crack then grows until it reaches the critical lengths input in the menu. Once the crack grows to the flange length, the growth rate is reset for the second growth rate associated with it growing along the web/flange connection. Once the crack reaches the limit state crack length, the year is tracked, recorded and marked as the year of unsatisfactory performance. This is done for each iteration with the results tabulated in a separate output file.

C) Baseline Condition. The baseline condition is generally the way that maintenance is performed at each project today. This is typically inspection and repair during scheduled dewaterings with no overall improvement to the overall reliability of the gates. The baseline condition for the miter gates assumes that the structure does not receive any major rehabilitation, painting, or repairs from the start of operation to the end of study period, unless the miter gates have been painted prior to present day. The baseline condition also assumes a paint life of 20 years and that corrosion of the girder members occurs over the remaining study period, unless it has been totally sandblasted and painted.[5] The corrosion rate is always assumed to be for a submerged structure since the portion of the gate that is being investigated is below lower pool.

D) Calibration of HWELD Reliability Model**.** The calibration of the HWELD reliability models was made based on field data of crack lengths for Markland. These measurements and repairs were taken at two points in time (1994 and 1996) during lock dewaterings to fix and repair cracks in the welds in the pintle area. Since the HWELD program is based on the realistic flange stresses for the head values of the miter gates at Markland, the crack lengths and expected probability of failures determined from the model match well and support the field data.

6.2.10 HWELD Reliability Model Results and Event Trees

The engineering team is required to take the results from the reliability model, which are hazard functions for time dependent components, and supply them to the economics team for their analysis. Additionally, the engineering team supplies an event tree for each component that is used in conjunction with the reliability analysis for the economists to measure the economic impacts associated with each component.

A) Baseline Condition for Miter Gates. The baseline condition represents a fix-as-fails plan in regards to the reliability analysis. It is assumed that any repairs that are done to the miter gate during normal scheduled dewaterings do not upgrade the reliability of the miter gate because these repairs typically only consist of replacing pintles, miter and quoin blocks, etc. These repairs do not effect the reliability of the miter gate based upon the limit state set up in reliability model. Therefore, the reliability of the structure is allowed to degrade through time without repairs under the baseline condition.

For the purposes of this study, the hazard function is defined as the probability of unsatisfactory performance in a given year assuming it has survived up to that year. The formula for this is depicted below:

h(t) = number of failures in year t / number of remaining survivors up to year t

The computation of *h(t)* yields a yearly probability of unsatisfactory performance given that the miter gate has survived up to that particular year. The probability of unsatisfactory performance is tied to the limit state for the component (i.e. critical crack lengths reached on two lower girders for the horizontally-framed miter gates).

B) Baseline Condition Event Tree. The baseline condition is the scenario upon which all without and with project alternatives are compared. The event tree for the miter gates was assumed to be the same for all projects. Assuming the limit state for the miter gates as described previously, the event tree shown in Figure 6.2.10.A was developed for the horizontally-framed miter gates. Regardless of the level of damage selected, the event tree

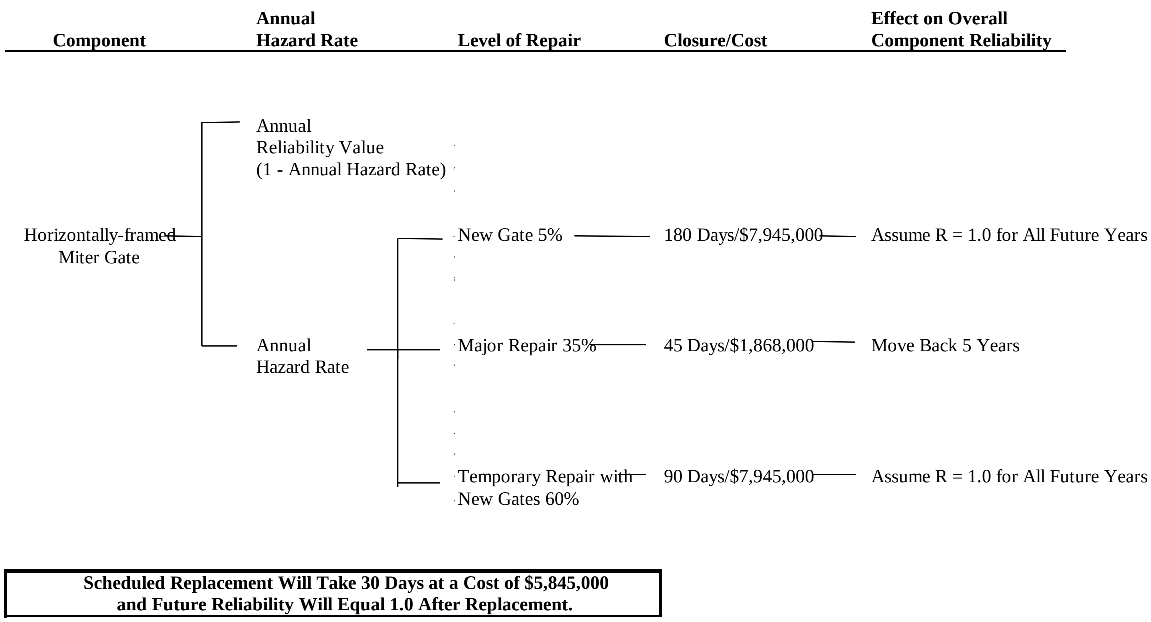

Figure 6.2.10.A Horizontally-Framed Miter Gate Event Tree

represents a fix-as-fail scenario for the baseline condition. Thus, the repair is only initiated in the economic model once the gate "fails". Because the gates for both the main and auxiliary chamber are the same design and construction technique, the same event tree is used for both the main and auxiliary chambers. However, economic results will differ for the auxiliary and main chambers as a function of navigation traffic and the hazard rates. The first branch of the event tree represents the annual hazard rate for the miter gates. The hazard rate changes depending upon the chamber which is being investigated. The second branch is the various options associated with the level of repair for the miter gates. Since the limit state is based upon a major failure, minor repairs were neglected in the event tree. The group decided that minor repairs to the miter gates are taken care of during normal maintenance dewaterings and they do not affect the overall gate reliability. The percentages associated with each level of repair were determined from engineering judgment in consultation with Operations personnel. Associated with each of these repairs is a repair cost and chamber closure time. The disbenefits associated with the chamber closure are modeled in the economic analysis by way of closure delay curves. Finally, the last branch updates the reliability in the next year based upon the repair. A further breakdown of the event tree from the level of repair forward is provided below.

Catastrophic Failure, Install New Gates. This repair assumes the most catastrophic event, a total failure of one of set of miter gates that is not repairable to the point that the chamber can be made operational. This repair assumes a new set of miter gates is fabricated, delivered, and installed within 180 days. Additionally, a repair cost of $7,945,000 is assumed for this repair. It is known that the Louisville Operations Repair Fleet costs on average about $35,000 per day including materials for repair work. The assumption is made that the repair fleet would need to be on-site for half the entire closure period. Additionally, the Ohio River Lakes and Rivers Division (LRD) gatelifter crane will cost about $6,500 per day. It would only be required about 30 days. Therefore, the repair costs for the new gate repair level is determined as follows:

Operations Repair Fleet Daily Cost: $3,150,000 ($35,000 per day for 90 days)

LRD Gate Lifter Crane:	\$ 195,000 (\$6,500 per day for 30 days)
Assembly Area Construction	\$ 600,000
New Set of Miter Gates Built & Delivered:	\$4,000,000 (fabrication, delivery new gates)
Total for All Items:	\$7,945,000

Because this is the most unlikely of the three chosen repair scenarios, the team only placed 5% on this level of repair. Future reliability of the miter gates would be considered to be 1.0, since the new gates would be installed by the next year and these would not be prone to the same type of problem as the present gates.

Major Repair. This repair assumes the gates have major damage, but can be repaired to the point that new gates are not immediately needed. Therefore, the closure time is reduced to 45 days with a repair cost of \$1,868,000. This cost is developed from the repair fleet rate (\$35,000 per day) plus the LRD gatelifter crane (\$6,500) per day. Since the existing gates are placed back in service, it is assumed that the reliability has the net effect of pushing the hazard rate back to the value from 5 years previous to the unsatisfactory performance. This was an easy way for the economists to upgrade the reliability of the gates within their model based upon a lower level of repair than a new component. It was assumed that this level of repair is much more likely than a new set of gates, but less likely than the temporary repair with new gates in the following year. Therefore, it is assumed that this option would be selected 35% of the time.

Temporary Repair with New Gates Following Year. The group envisioned the most likely repair scenario to be the one where the gates suffer major damage, but can be "patched up" to the point that the chamber is operational. However, the damage is too great to risk having the gates used for an extended period. Therefore, new gates are constructed and delivered to the site for installation by the following year. The repair cost associated with this alternative is assumed to be \$7,945,000, but the chamber is closed only for 90 days. The closure is assumed to occur in two phases. An initial 45-day dewatering for the repair to the existing set of miter gates to get the chamber operational. Another 45-day dewatering then is required later in the same year to install the new set of gates. Therefore, there is 90 days of repair fleet time at the lock at \$41,500 per day including the LRD gatelifter crane. The team thought this was the most likely repair scenario given a "major" unsatisfactory performance event and placed 60% on this level of repair.

A final piece of information the engineering team supplied in the event tree was the cost of a scheduled replacement for a set of miter gates. This assumes that the miter gates have not failed up to this point and the chamber is operational when the gates are replaced with new ones. Because the replacement is scheduled in advanced and preliminary work is completed prior to dewatering the chamber, the chamber closure time and "repair" cost is reduced when compared to replacing the gates only after they fail. The estimated cost of \$5,845,000 includes \$4,000,000 for a new set of gates and \$1,245,000 to install them. Additionally, a cost of \$600,000 is assumed for the assembly area. The economists will use the scheduled, advanced replacement cost and closure in their analysis to determine if it is more economical to replace the miter gates in advance before they perform unsatisfactorily. The scheduled replacement cost is shown in the event tree branches in Figure 6.2.10.A.

6.2.11 Miter Gate Reliability Results for Group 1 Projects

Referring back to Figure 6.2.1.A, the miter gates represented in Group 1 include both chambers at Willow Island, Belleville, Racine, Greenup, and Markland. Additionally, the main chamber miter gates at McAlpine are included (the auxiliary chamber at McAlpine is schedule for replacement within 5 years). The McAlpine existing main chamber miter gates were not included in the analysis because a replacement set of gates for the chamber is presently under construction. Again, the global finite element model for this group was based upon the miter gates at Markland. Because of the historical performance at Markland, an excellent model was developed because both the finite element model and reliability model could be calibrated upon the field measurements at Markland. In general, the hazard rates for the group 1 miter gates are the highest relative to the other groups because the projects are generally older and have seen more cycles. Additionally, some of these gates were designed with older criteria and are less "stout" than some of the newer miter gates. Because several of these sites have hazard rates that are close in value, only a few can be depicted in one graph so they will not overlap. The graphs represent the probability of unsatisfactory performance (vertical axis) versus years (horizontal axis). Several graphs will be used to depict the hazard rates for the group 1 miter gates. Figure 6.2.11.A depicts the hazard rates for the gates at Markland and Racine. The hazard rate for the auxiliary chamber at Racine was insignificant from an economic standpoint and therefore is not shown graphically. This is due to the low historic number of cycles and projected cycles for the Racine auxiliary chamber.

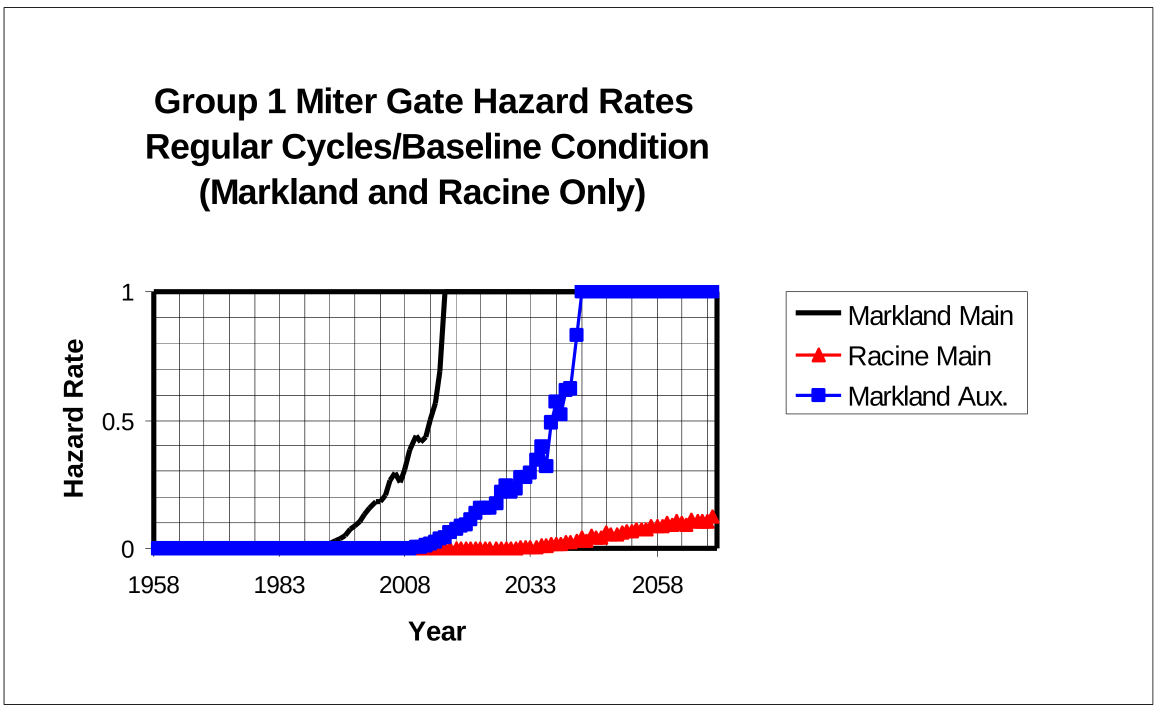

Figure 6.2.11.A Markland and Racine Miter Gate Hazard Rates

Figure 6.2.11.B depicts the hazard rates for the miter gates at Greenup and Belleville. Both chambers are shown for Greenup, but only the main chamber at Belleville had a significant hazard rate through the study period.

Figure 6.2.11.C illustrates the hazard rates for the miter gates at Meldahl and Willow Island. It is tough to see on the figure, but the annual hazard rates for the Meldahl auxiliary chamber is approximately the same as the Willow Island main chamber.

As evidenced by the graphs for group 1, the miter gates at Markland, Meldahl, and Greenup represent the highest hazard rates. All three of these projects are older than the other projects and have had historically higher navigation traffic relative to the other group 1 sites. Therefore, each of these projects have had significantly more operating cycles to date. Additionally, each of the gates at these three sites was designed under a little less stringent criteria since they are older and generally do not have plates as thick as other projects (note general flange plate thickness of group 1 miter gates relative to the other groups). Also, the field experience at Markland provided extremely beneficial information relative to calibrating these models given the current condition of the miter gates. As expected, the main chamber miter gates have higher hazard rates when compared to the auxiliary chamber gates.

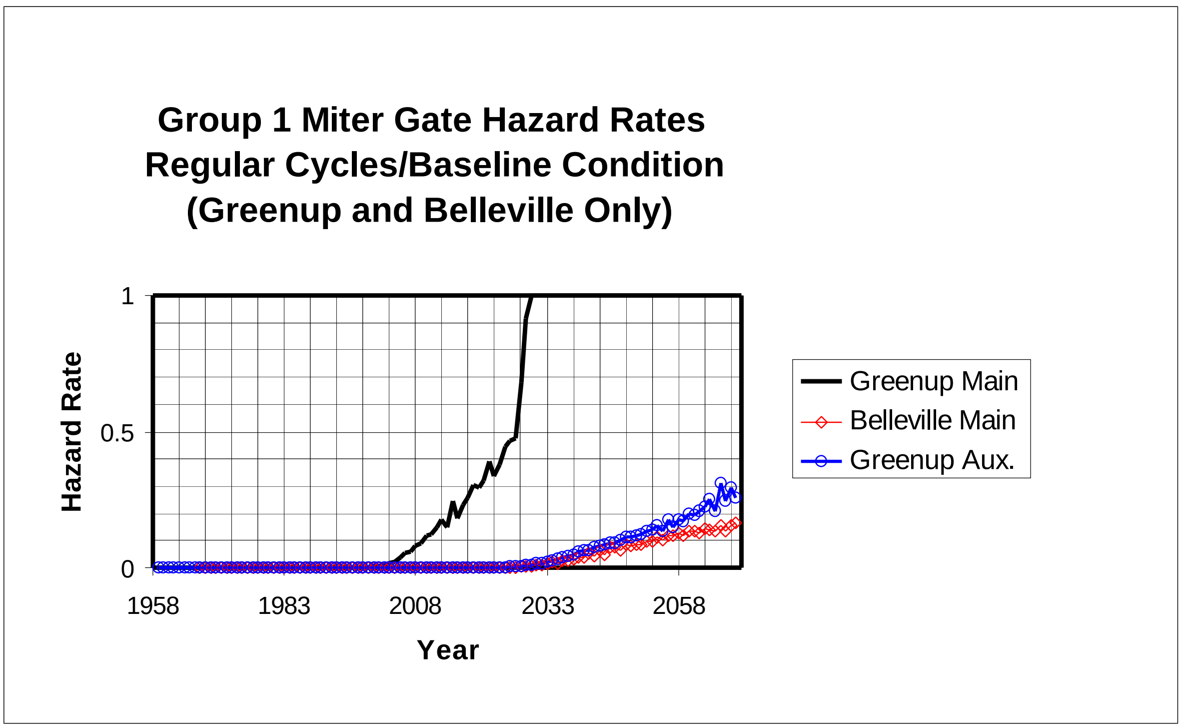

Figure 6.2.11.B. Greenup and Belleville Miter G ate Hazard Rates

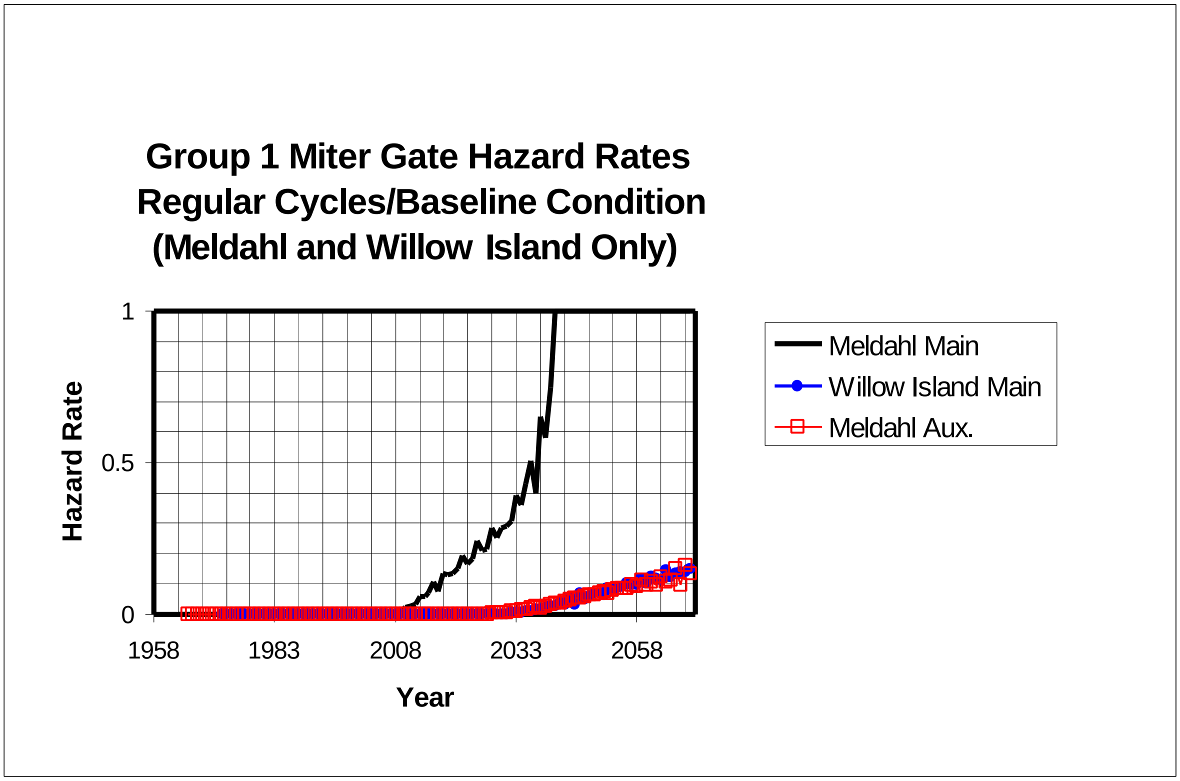

Figure 6.2.11.C Meldahl and Willow Island Miter Gate Hazard Rates

6.2.12 Miter Gate Reliability Results for Group 2 Projects

The miter gates represented in Group 2 include the main and auxiliary chamber gates at New Cumberland, Pike Island, and Hannibal. The difference between these gates when compared to group 1 are they have fixed, bolted pintles with two diagonals per leaf. The group 1 gates had floating, welded pintles with only one diagonal per leaf. Additionally, at New Cumberland and Pike Island, the upstream and downstream miter gates within each chamber are different because the sill heights vary. Another difference relative to the modeling is the limit state for the group 2 miter gates (as well as stress concentration factors) is different than group 1. The downstream miter gates at New Cumberland were considered the most critical given information from recent dewatering inspections. Therefore, these gates were selected to be the global finite element model representative of all group 2 miter gates. Because the miter gates within each chamber were different, separate hazard rates for Pike Island and New Cumberland had to be developed. Because several of these sites within group 2 have hazard rates that are close in value, only a few can be depicted in a single graph so they will not overlap. The graphs represent the probability of unsatisfactory performance (vertical axis) versus years (horizontal axis). Several graphs will be used to depict the hazard rates for group 2 miter gates. Figure 6.2.12.A depicts the hazard rates for the miter gates at New Cumberland.

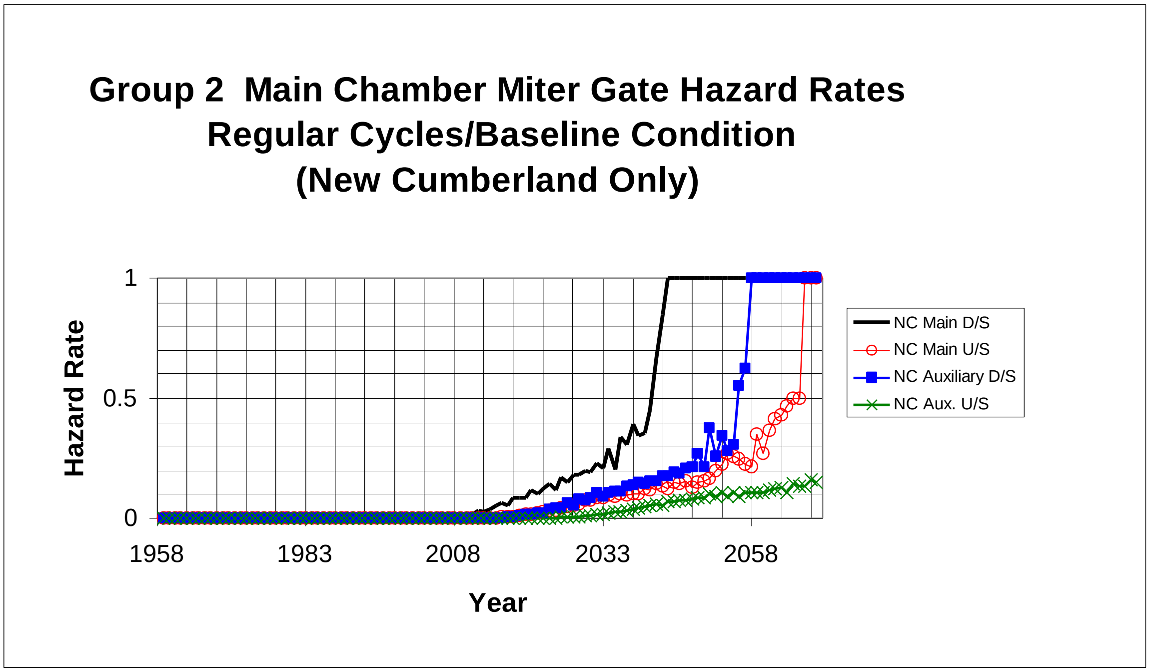

Figure 6.2.12.A New Cumberland Miter Gate Hazard Rates

Figure 6.2.12.B represents the hazard rates for the miter gates at Pike Island. These are similar to the ones developed for New Cumberland, however, the trend between the two sites is different. This is mainly due to the lesser differences between the upper and lower miter gates at Pike Island compared to the differences between the same chamber gates at New Cumberland. The hazard rates for the gates at Pike Island are lower than those at New Cumberland. Recent inspections confirm that the miter gates at Pike Island are in better condition compared to the gates at New Cumberland. Only the upstream auxiliary gates at Pike Island are shown because the downstream auxiliary gates have essentially the same values with respect to showing the values graphically.

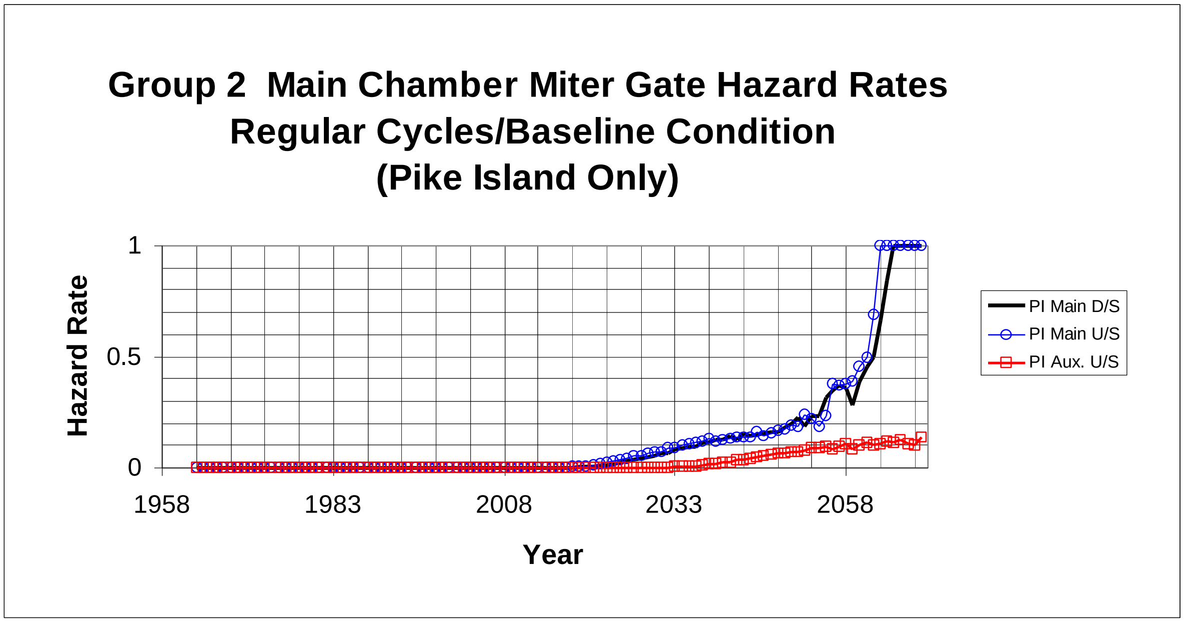

Figure 6.2.12.B Pike Island Miter Gate Hazard Rates

The results for the hazard rates at Hannibal were being refined at the time of the interim report due to a previous error that was found in the input file for that site. The results will be incorporated into the final ORMSS report.

The group 2 miter gate hazard rates seem to compare well together with one another. The New Cumberland gates have the highest hazard rates relative to the gates at Pike Island and Hannibal. This is confirmed from recent dewatering inspections that have shown significant cracking of the New Cumberland miter gates. The miter gates at Hannibal have the lowest hazard values because the operating cycles are the lowest in the group and the gates are the newest of all group 2 miter gates. These results indicate that the reliability model is providing accurate data within the confines of the modeling effort itself.

6.2.13 Miter Gate Reliability Results for Group 3 Projects

The miter gates represented in Group 3 are generally the newest gates on the Ohio River, generally constructed in the early to mid 1970's. The sites include Cannelton, Newburgh, J.T. Myers (formerly Uniontown), and Smithland. R.C. Byrd and Olmsted are also lumped into this category but are so new and designed with large load factors that reliability model results indicate no reliability problems for the selected group 3 limit state throughout the study for these projects. Figure 6.2.1.A depicts the characteristics of group 3 miter gates. These are the same as group 1 gates except the pintle is bolted and not welded. Additionally, thicker plates are used in design reducing the operating stresses, thus, generally causing lower hazard rates over time. These gates also followed the limit state criteria set up for the group 2 gates, which is cracking of the girders at the end of the quoin diagonal plate.

All of the hazard rates for the group 3 miter gates are shown in Figure 6.2.13.A. Only the main chamber at Cannelton and both chambers at Smithland had hazard rates that were significant from an economic standpoint. Reviewing the properties of the gates shows similar plate sizes, however, the lift at Cannelton is 25-feet under normal pool conditions. This is much higher than the 16-ft lift at Newburgh and 18-ft at J.T. Myers, therefore, the operating stresses on the Cannelton miter gates is higher than those at Newburgh and J.T. Myers. That is why the hazard rate of the Cannelton main chamber miter gates is significant when compared to those at Newburgh and J.T. Myers. Smithland likewise has to withstand a larger hydrostatic head (22 feet for normal pool levels) and always sees more operating cycles compared to the other group 3 projects. It is important to note that both chambers at Smithland are 1200 feet in length. Thus, both chambers see a significant amount of cycles and there is not a "typical" auxiliary chamber at this site.

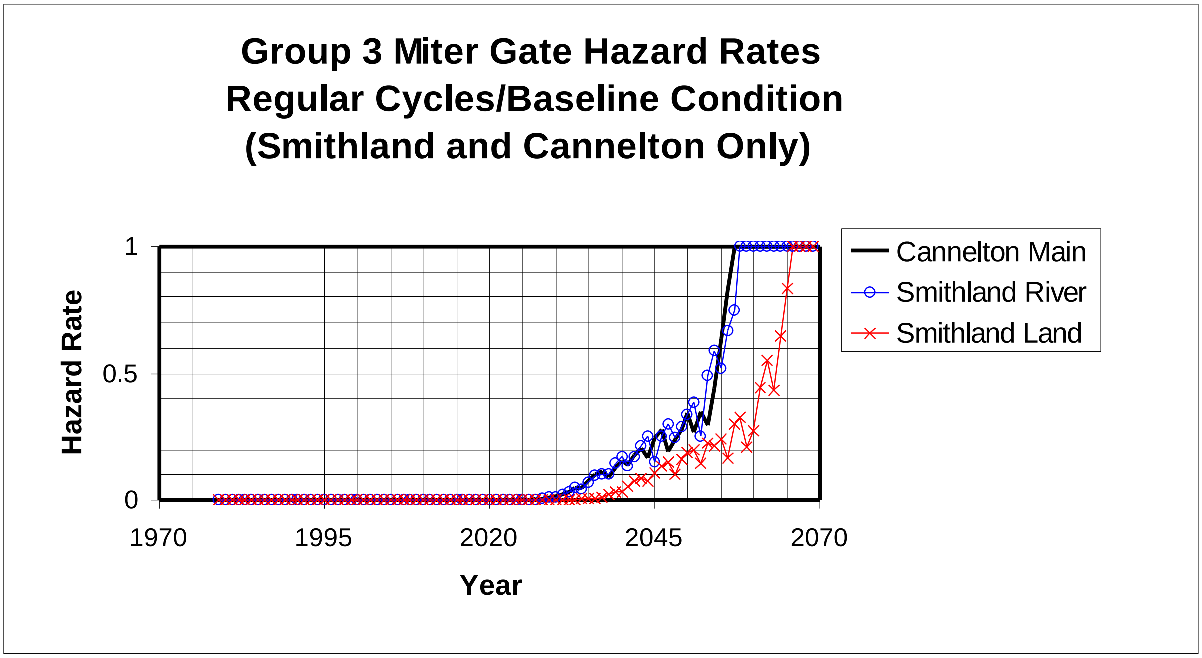

Figure 6.2.13.A Smithland and Cannelton Miter Gate Hazard Rates

6.2.14 Economic Analysis of Horizontally-Framed Miter Gates

Using the miter gate hazard rates for each chamber and the event tree depicted in Figure 6.2.10.A, a direct comparison can be made between fixing the gates after failure or replacing them on a scheduled basis prior to failure. The economists use the data provided by the engineering team to determine average annual costs associated with the fix-as-fails condition versus replacing the gates prior to failure at selected dates. Each of the average annual costs associated with the baseline condition (fix-as-fails) is compared to different replacement dates to determine the lowest average annual cost. The option with the lowest average annual cost sets the timed replacement of the miter gates. If justified, this closure is then input into the cost and closure matrices in the year with the lowest average annual cost. If the lowest average annual cost is associated with the baseline condition (fix-as-fails) then the replacement of the gates is not justified economically and no replacement closure is projected into the matrices for the economic analysis. However, any costs associated with the probability of unsatisfactory performance for non-justified miter gates are included in the overall economic analysis. This is done for each chamber independently.

Table 6.2.14.A summarizes the average annual costs associated with the miter gates for both the main and auxiliary chambers at all ORMSS projects. There are a few miter gates where final revisions of the miter gate reliability economic analysis has not been completed at the time of this interim report but will be included as part of the final ORMSS report. These include the Hannibal miter gates and some of the miter gates at Pike Island and New Cumberland.

Table 6.2.14.A Average Annual Cost Associated with Miter Gates.

Average Annual Costs of Horizontally-Framed Miter Gate Reliability												
		Replacement Dates Tested in the Economic Analysis										
Project	**Chamber**	**Fix-As-Fails**	**2000**	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2050**
New Cumberland	Main D/S	$555,100			$376,900	**$330,200**	$363,600	$422,800				
	Main U/S											
	Aux. D/S			Economic Analysis of Reliability Results Still Being Refined								
	Aux. U/S											
Pike Island	Main D/S	$455,400					$261,600	**$223,600**	$238,700		$347,100	
	Main U/S			Economic Analysis of Reliability Results Still Being Refined								
	Aux. D/S	**$24,800**									$46,800	$32,700
	Aux. U/S			Economic Analysis of Reliability Results Still Being Refined								
Hannibal	Main			Economic Analysis of Reliability Results Still Being Refined								
	Auxiliary			Economic Analysis of Reliability Results Still Being Refined								
Willow Island	Main	$99,700							$99,300		**$64,400**	$77,800
	Auxiliary	**$0**										$23,300
Belleville	Main	$307,600					$256,000		**$153,500**			$251,000
	Auxiliary	**$0**										
Racine	Main	$214,000					$278,900		$156,100		**$121,300**	$170,200
	Auxiliary	**$0**										
R.C. Byrd	Main	**$0**										
	Auxiliary	**$0**										
Greenup	Main	$8,718,800	$1,375,800	**$1,332,200**	$2,084,400		$6,229,900					
	Auxiliary	$269,300	$645,000		$338,800		$172,100		$94,000	**$80,800**	$87,200	$173,900
Meldahl	Main	$5,237,200		**$1,216,000**	$1,221,600	$1,652,200	$2,649,100					
	Auxiliary	$130,500					$172,500		$92,500		**$62,700**	$80,600
Markland	Main	$4,154,400	**$1,178,000**	$2,173,700	$3,235,700							
	Auxiliary	$296,200			$452,900	$336,100	$279,900	**$267,000**	$270,800			
Cannelton	Main	$3,170,900					$779,100		**$627,600**		$1,662,400	$2,816,700
	Auxiliary	**$4,000**							$91,800		$48,700	$26,900
Newburgh	Main	**$2,600**							$743,100		$496,700	$332,900
	Auxiliary	**$0**										
J.T. Myers	Main	**$45,000**							$854,300		$821,900	$914,500
	Auxiliary	**$0**										
Smithland	Landward	$1,472,900					$375,100		**$250,200**		$270,600	
	Riverward	$1,787,700					$272,500		**$211,100**		$732,600	$1,558,200

The results show the lowest average annual costs for the chamber specific miter gates in bold numbers in the table. For example, the lowest average annual cost for the main chamber miter gates at Cannelton is $627,600 in the year 2030. This value compares to the fix-as-fails average annual cost of $3,170,900 for the same set of miter gates and an average annual cost of $779,100 and $1,662,400 to replace the gates in 2020 and 2040, respectively. Therefore, the most economic time to replace the main chamber miter gates at Cannelton is around the year 2030. Without "fine-tuning" the replacement date, the values shown are accurate to within a few years. The same logic follows for all other sites. When the fix-as-fails cost is the lowest, there is no economically justified time to replace the miter gates. Values of $0 for the fix-as-fails case indicate that the miter gates were 100% reliable for the selected limit state through the year 2050. Therefore, there is no justified replacement date for these miter gates. For sites with economically-justified replacement dates in the near future (prior to 2015), a further economic analysis was done to fine tune the date of replacement. The results of the further analyses indicate that the following replacement dates are optimally-timed:

Markland main chamber gates in 2001

Meldahl main chamber gates in 2008
Greenup main chamber gates in 2004

The replacement closures were input into the cost and closure matrices at the appropriately justified date. Since the hazard rates reflect only a single set of gates and most sites have the same gates at the other end of the chamber, consecutive closures were placed in the matrix for replacement of both sets of miter gates. For example, the Markland main chamber gates were justified for replacement in 2001, therefore, a 45 day closure was placed into the main chamber for replacement of the upper gates. The following year, 2002, another 45 day closure was added into the matrix for replacement of the lower miter gates. See the cost and closure matrices for other replacement dates.

6.2.15 References for Horizontally-Framed Miter Gate Reliability

1. "Fatigue Cracking Evaluation of the Markland Miter Gates," ANATECH Report ANA-96-0201 to Corps of Engineers, Louisville District, November 1996.
2. American Society of Mechanical Engineers Boiler and Pressure Vessel Code, 1989 Edition, American Society of Mechanical Engineers, July 1989.
3. "Structural Inspection and Evaluation of Existing Welded Lock Gates," U.S. Arms Corps of Engineers, ETL-1110-2-346, Sept. 1993.
4. Ellingwood, Zheng, and Bhattacharya. “Reliability-based Condition Assessment of Steel Miter Gates,” Final Report Submitted to Black & Veatch Engineers, March 1996.
5. “Reliability Analysis of Hydraulic Steel Structures with Fatigue and Corrosion Degradation,” WES Report, March 1994.

6.3 VERTICALLY-FRAMED MITER GATE RELIABILITY

There are only three projects on the Ohio River that utilize vertically-framed miter gates. These are the upper three sites on the Ohio River: Emsworth, Dashields, and Montgomery (EDM) Locks and Dams. Additionally, only the main chamber at these sites have vertically-framed miter gates, the auxiliary chamber at each site has horizontally-framed miter gates. Therefore, out of 38 lock chambers on the Ohio River, only 3 use vertically-framed miter gates. However, since this is a major component that can potentially have major consequences, a reliability model was developed for vertically-framed miter gates.

6.3.1 Background of Upper Three Projects (EDM)

The upper three Ohio River projects, EDM, are the oldest operating locks and dams on the Ohio River. These projects were built in the early 1920's and 1930's. The oldest is Emsworth which was completed in the early 1920's. Because of overall deteriorating conditions at each of the three projects, the locks at each site were rehabilitated in the mid-to-late 1980's. All major components, with the exception of dam gates and concrete, were replaced as part of this rehabilitation. Included in the work was the replacement of the existing main chamber, vertically-framed miter gates with newer, stronger vertically-framed miter gates. The existing, original miter gates were constructed of riveted, plate girders. The new miter gates installed during the rehabilitation are made of rolled wide flanged girders. This makes a significant difference in the reliability of the miter gates. Additionally, the new miter gates were considerably stronger in terms of the section modulus when compared to the older gates. The new gates are stressed considerably lower in terms of bending and shear under normal operating loads. This is a controlling factor in the fatigue analysis.

6.3.2 Background of Vertically-Framed Miter Gate Reliability Model

The reliability model for the vertically-framed miter gates was the Corps of Engineers first attempt to develop time dependent hazard functions for lock structures for the purpose of subsequent economic analysis. Therefore, the engineering team was required to develop the proper methodology for developing hazard functions for lock and dam components. The vertically-framed miter gates were selected first because a preliminary reliability assessment of the original vertically-framed miter gates at Emsworth had already been investigated by Dr. Bruce Ellingwood of Johns Hopkins University for the Pittsburgh District. The model that Dr. Ellingwood developed was based upon the limit state of fatigue of the main load bearing beams.[1] The ORMSS engineering team's first goal was to attempt and develop a reliability model for the vertically-framed miter gates using Dr. Ellingwood's previous work as a basis. The insight and guidance provided by Dr. Ellingwood's model proved to be quite valuable in the initial modeling efforts. However, some changes were required to the model developed by Dr. Ellingwood in order to establish the necessary parameters that could be used for all three upper Ohio River sites. The engineering team developed its initial model using the parameters from the older, built-up girder miter gates that were in place from the early 1920's until the rehabilitation in 1984. Once the reliability results from the new model compared well with the newly adjusted results from Dr. Ellingwood's model, the team believed it had a model that was accurate within the confines of the analysis itself. This model was then used for the analysis of the new vertically-framed miter gates at EDM to determine their time dependent reliability.

6.3.3 Vertically-Framed Miter Gate Reliability Model Development

The vertically-framed miter gate model is quite different from the horizontally-framed miter gates. Whereas an original, Ohio River specific Visual Basic coded model was developed for the horizontally-framed miter gate reliability model, the spread sheet Microsoft Excel™ was used in conjunction with the Monte Carlo simulation software, @Risk™ for the vertically-framed miter gate reliability model. Additionally, the limit states selected for the vertically-framed miter gate model were the strength and fatigue of main, load carrying beams and the top horizontal girder. The horizontally-framed miter gate limit state was selected based upon field experience of fatigue cracking at specific connections around the pintle region of the gate. There are a couple of reasons that the process selected for the vertically-framed miter gates was chosen. Foremost, the process and limit state for the vertically-framed miter gates was the same one as Dr. Ellingwood had used in his previous modeling efforts. Since he had credible results, the engineering team wanted to calibrate the new model versus his initial results since this was the first attempt to develop a truly time dependent model.

6.3.4 Vertically-Framed Miter Gate Reliability Model Details

Probabilistic evaluation of the structural components was performed with the aid of spreadsheet and a simulation program. Variables were treated as random where needed with appropriate values obtained from either the literature, past records or a combination of calibration and engineering judgment. The model consists of a workbook within a spread sheet. The overall spread sheet contains four separate sheets defined as *Inputs, Outputs, Horizontal Girder,* and *Vertical Beam*. The *Horizontal Girder* and *Vertical Beam* sheets are the where the computations for the reliability of the structure take place. The model tracks both the performance of the miter gate from a strength standpoint (load vs. capacity) and fatigue standpoint (when the number of *unfactored* allowable cycles is reached).

Inputs Sheet

This sheet contains all the input parameters for the model. Fixed values such as top of miter gate and miter gate sill elevations were obtained from the as-built drawings. Examples of random variables used are the yield strength of steel, structural analysis factor, corrosion variables, fatigue strength and tail water elevation. During each iteration, a new set of random values is generated. Each iteration tracks the miter gate through the study period until either a limit state is reached or the end of the study period is reached without a failure. Once either of these occurs, a new iteration is begun with the selection of new random variables. A simulation is completed once all the pre-selected number of iterations is completed. The tail water elevation is generated once at the beginning of each iteration and is kept constant for the life span (study period) of the structure for that particular iteration. A brief description of the variables used is provided below.

Pool Elevations. Tail water elevation is taken as a random variable and the upper pool is kept constant. Daily pool records are readily available at all ORMSS sites from Lock Performance Monitoring System (LPMS) data from about 1982 to present. The differential head is used for checking the bending limit state for both the strength and fatigue modes. Since the hazard function is developed on an annual basis, the strength mode of the model required the maximum annual head differential since that occurred each year. This was the load that was computed for each year for the strength limit state. For the fatigue limit state, a histogram of number of lockages versus differential head was built from LPMS data. This histograms yields actual number of operating cycles versus differential heads for various ranges.

Material Data. Statistics for yield strength were obtained from the literature and steel yield strength is generated once at the beginning of each iteration. Fatigue capacity (factor log c) was treated as a random variable and generated for each iteration. Another factor that was treated random is the corrosion rate, which depends on the material and the surroundings. Corrosion rate is different for atmospheric, splash and submerged regions. All random variables were selected once at the beginning of each iteration and kept constant throughout that particular iteration.

Corrosion. The cumulative number of years during which corrosion takes place is referred to as the variable t. Note that periodic painting affects the corrosion rate and must be taken into account in the analysis. In the analysis, corrosion is treated as a random variable. Taking corrosion as:

$$C(t) = At^B$$

where the penetration rate, C(t), with units of μm/year, is expressed as a function of time. The variable A, the rate parameter, is log-normally distributed with a mean, $\mu = 140$, and standard deviation, $\sigma = 42$, for the splash zone. The constant B, the time-order parameter, is an experimentally observed parameter and is treated as a deterministic value equal to 2/3.[1] Knowing the thickness at time t, the section modulus, S(t), with respect to time in terms of a variable flange and web thickness is computed.

Fatigue. Fatigue damage is based on the S-N curve and the data available in the literature, where S represents the stress and N represents the number of allowable cycles.

$N = C / (\text{stress range})^m$, where
N = allowable cycle
C = variable depending on weld type
m = experimentally observed constant

Variable C is treated as random; statistics of C were taken from literature and is dependent upon the type of existing welded connection.

Hydraulic Cycles. Available records of lockages were used to obtain the hydraulic load cycles on the structure from installation through the present date. A load cycle is referred to as a complete filling and emptying of the chamber. For the future years, forecast by the economists must be provided to determine future reliability.

Analysis Factor. The moment demand is variable because of assumptions and inaccuracies in analytical procedures. This can be introduced by the factor B(I), which is log-normally distributed with mean, $\mu = 0.964$, and standard deviation, $\sigma = 0.12$. B(I) is an experimentally determined value for a vertical beam in a vertically framed miter gate. The value for B is different for the horizontal girder.[2]

Computation Sheets

The computations are carried out in two sheets, *Horizontal Girder* for the top girder and *Vertical Beam* for the vertical beams that transfer loads to the top horizontal girder. There are two failure modes (i.e., limit states) for both the vertical beam and horizontal girder, namely strength (in bending) and fatigue. Both modes consider the cumulative effect of corrosion and the paint history of the respective site. Calculations are performed in a similar manner for both components.

Random variables are first generated at the beginning of each iteration in the *Inputs Sheet*. For each iteration (i.e., life span of the structure), the properties are calculated considering the changes in dimensions due to corrosion and paint history.

The strength mode limit state was defined by mid-girder flexure for both the vertical beam and horizontal girder. For both the beam and the girder, the limit state is defined as “demand exceeds capacity.” There are no safety factors or other criteria applied to either the demand or capacity side of the equation. The capacity is determined for each iteration by the random variable selected for the yield strength of the steel and the amount of corrosion on the structure. This is checked against the demand from the load and if the demand exceeds the capacity any time, the year it occurs is noted for each iteration. At the end of a simulation, annual unsatisfactory performance occurrences are tabulated for each year and hazard functions are computed with the help of a macro.

The hazard function, h(t), is the negative derivative of the natural log of L(t), or:

$$h_t = -d(\ln L_t) / dt.$$

h(t), therefore, is the negative slope of the curve defined by the function ln (L(t)). In the literature, h(t) is defined as the conditional failure rate in a given time period. That is, hazard rate is the probability of an unsatisfactory performance within time increment *t*, given the structure has performed satisfactorily from time zero up to time *t*. The hazard function is computed numerically using the output data from simulation

The fatigue mode limit state is also defined by demand versus capacity. Demand is the cumulative effect of fatigue damage at the mid-span for the beam connection type. Fatigue damage was defined as the ratio of actual number of load cycles to allowable number of load cycles for a constant amplitude loading. The stress that causes the fatigue is not constant for all load cycles. Thus, a head versus percentage of operating cycles histogram was built based on the LPMS data for each of the three project main chamber locks. The histogram partitions the total number of load cycles into appropriate stress categories. The standard Miner's Rule is used to sum the fatigue damage of variable amplitude loading and it is considered unsatisfactory when the cumulative damage exceeds unity. Similar to the strength case, macros in the spreadsheet are used to calculate the hazard function for the fatigue mode.

Outputs Sheet

The *Outputs* worksheet lists the time-dependent reliability and hazard rates for the two limit states considered for each of the component, fatigue and strength of both the vertical beam and horizontal girder. Graphs are also provided once the computation of the hazard function is completed in this worksheet. These results are sent to the economists when appropriate along with an event tree.

6.3.5 Model Results and Conclusions

The model was built for the purpose of determining time dependent reliability of vertically-framed miter gates. Once the model was completed, the first item to "test" was the performance of the original Emsworth upper, main chamber miter gates. These gates were installed when the structure was built in the early 1920's. They were replaced during the rehabilitation of the Emsworth project in the early 1980's. It is known that the original miter gates were in very poor condition when they were replaced. Therefore, the actual reliability of the original miter gates was quite low when they were replaced. After making the appropriate adjustments during the construction of the model, the original miter gates at Emsworth were tested with the new ORMSS vertically-framed miter gate reliability model to determine their time dependent reliability. The results were excellent. Using the correct date for historical painting dates and operating cycles, a high hazard rate was computed for the miter gates by the early 1980's. These results compared well with the results that Dr. Ellingwood had for the initial modeling effort once the proper results were made to that model.

With confidence that the new model was yielding accurate results within the confines of the analysis itself, the team collected the necessary information to make the reliability runs for the main chamber miter gates at EDM. It was evident once the initial results were computed that the hazard rate for the main chamber miter gates would be extremely low throughout the study period for each of the three projects. In reviewing the properties for the new gates, the team found the answer to why the hazard rate appeared to be so low. The new miter gates that were installed were vastly improved over the older design. The old miter gates were constructed of riveted, built-up plate beams and girders. For the limit states that we were investigating, these are the worst type of construction details for fatigue. The new gates (installed during the rehabilitation) were made of rolled wide flange sections. Additionally, the section modulus had been increased by over three times when compared to the original miter gate beams and girders.

Therefore, the model was giving correct values for the time dependent reliability of the vertically-framed miter gates for the selected limit states. The hazard rates were computed as zero for each of the main chamber miter gates. Without a hazard rate, the economists were not required to make an economic analysis of the vertically-framed miter gates, thus, an event tree was not required.

In conclusion, the replacement of the vertically-framed main chamber miter gates for the selected limit states is not justified during the study period at any of the three projects. This does not indicate that there will never be any problems associated with the miter gates. Operational problems will be encountered, but repairs are handled through normal and major maintenance.

6.3.6 References

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2. Padula, J., Chasten, C., and Mlakar, P. (1995): Reliability of Hydraulic Steel Structures with Fatigue and Corrosion Damage. CESEC 1995.

3. EM 1110-2-2703 (1994): Lock Gates and Operating Equipment

4. Ellingwood, B.R. (1993) Load and Resistance Factor Design for Steel Miter Gates, CEWES Instruction Report ITL-93-4.

5. Commander, B.C., Schulz, J.X., Goble, G.G., and Chasten, C.P. (1993) Computer-Aided, Filed-Verified Structural Evaluation, Report 3, Field Test and Analysis Correlation of a Vertically Framed Miter Gate at Emsworth Lock and Dam, CEWES Technical Report ITL-92-12.

6.4 HORIZONTALLY-FRAMED REVERSE TAINTER CULVERT VALVE RELIABILITY

Reverse tainter culvert valves at Ohio River projects are used to control the filling and emptying of lock chambers. All sites with the exception of the upper three (Emsworth, Dashields, and Montgomery Locks and Dams) utilize reverse tainter culvert valves for the filling and emptying of the lock chamber. Emsworth, Dashields, and Montgomery (EDM) utilize butterfly valves for the operation of their filling and emptying systems. Butterfly valves are covered within the overall mechanical model. There are two types of reverse tainter culvert valves: horizontally-framed and vertically-framed. Separate reliability models had to be developed for each of these reverse tainter culvert valves.

Most Ohio River projects use vertically-framed reverse tainter culvert valves, however, there are several sites with horizontally-framed valves. In general, the older sites use horizontally-framed culvert valves. These include the valves at Pike Island, New Cumberland, Greenup, Meldahl, Markland, and the existing main chamber at McAlpine. The newer projects have vertically-framed valves. These sites include Willow Island, Belleville, Racine, Hannibal, R.C. Byrd, Cannelton, Newburgh, J.T. Myers, Smithland, and Olmsted. This section will focus on the horizontally-framed culvert valves. Section 6.5 focuses on vertically-framed culvert valve reliability.

Due to schedule and funding constraints, only the horizontally-framed culvert valves for Markland and Greenup were totally completed (runs calibrated, through ITR, etc.) at the time of this interim report. Therefore, this section will only detail the results for these sites. The reliability assessments of the vertically-framed valves at Meldahl, Pike Island, New Cumberland, and the existing main chamber at McAlpine will be completed as part of the overall ORMSS final report. The reliability results for the valves at Markland and Greenup will be carried forward into the final ORMSS report.

The horizontally-framed reverse tainter culvert valves at Markland and Greenup have been in operation since the each lock commenced operations in the late 1950's. At both sites, the design and construction technique for both the main and auxiliary chamber valves are the same, therefore, the same reliability model can be used for each chamber with chamber specific input for historical painting and operating cycles. Additionally, the culvert valves at Greenup are the same design as those at Markland Lock and Dam, for which, a global finite element model was developed. It is important to note that the significance of an unsatisfactory performance of a reverse tainter culvert valve is quite different depending upon whether it occurs in the main or auxiliary chamber.

6.4.1 Main Chamber Versus Auxiliary Chamber

The main chamber at all sites, with the exception of EDM, has a total of four reverse tainter culvert valves for filling and emptying the lock, two filling and two emptying valves. One filling and emptying valve is in the middle wall and the other set is in the river wall. They can be operated independently. Therefore, a repair to one of the main chamber culvert valves does not necessarily close the chamber. It is possible to dewater the area around the valve only, thus, leaving the other filling and emptying set to operate the chamber. Filling and emptying time is roughly doubled over normal operation. Normal filling and emptying time for a typical 1200 foot lock on the Ohio River is approximately 8 minutes each.

For the auxiliary chamber, there are two valves to control filling and emptying operations. One filling and emptying valve each. Therefore, a problem with one of the valves on the auxiliary chamber closes the entire chamber while necessary repairs are made. The significance of closing the auxiliary chamber is considerably less than the main chamber, however, disbenefits associated with the closure can become large for extended closures.

6.4.2 Description of the Horizontally-Framed Culvert Valves

The valves are termed horizontally-framed since the main load from the skin plate is transferred to large vertical plate girders by a series of horizontal girders. The large vertical plate girders transfer the load to a series of axially-loaded strut arms that connect the body of the valve to a pin plate casting, which transfers the load to the valve's trunnion beam. The trunnion beam then transfers the load to the concrete monolith. The valves act in tension since the tainter gate is reversed to the direction of flow. Photographs of the valves at Markland, which is of the same design as Greenup, are shown in Figures 6.4.2.A through 6.4.2.E.

Because of the complexity of these structures and the potential redundancy associated with them, a global finite element model for the Markland culvert valve was developed to determine possible areas of high stress. Additionally, the problems associated with the miter gates caused concern for the valves since these structures also had large amounts of welding that may lock in residual stresses. It was determined from the finite element modeling that there were two areas on the valves that suggested areas of high stresses during normal operation. The two locations were where the strut arm transitions and connects to the pin plate casting. The other location was where the horizontal girders are connected to the vertical plate girders. It was decided to concentrate on the strut arm connection since there is little to no redundancy associated with this connection. Additionally, Louisville District Operations personnel familiar with the Markland culvert valves have stated that this connection has caused concern over the years.

Figure 6.4.2.A. Side View of Markland Reverse Tainter Culvert Valve

6.4.3 Finite Element Modeling of the Culvert Valves and Calibration

The same basic procedure and steps used to develop reliability models for fatigue cracking at welded connections for the miter gates were employed for the reverse tainter culvert valves. The differences are that, for the culvert valves, direct tensile loads act on structural members and connections, and that the impinging water loads are significant, both in amplifying the load and in area reduction due to erosion-corrosion effects (note pitting of strut arm in Figure 6.4.2.D). To compensate for these effects, the design of culvert valves use a much higher factor of safety by increasing load factors for design loads and reduced design stress allowables. The development of the reliability model requires the same basic steps of characterizing crack initiation, crack growth rate, and definition of the limit state but requires different criteria and methods.

Figure 6.4.2.B. Front View of Markland Reverse Tainter Culvert Valve.
Note surface deterioration of skin plate

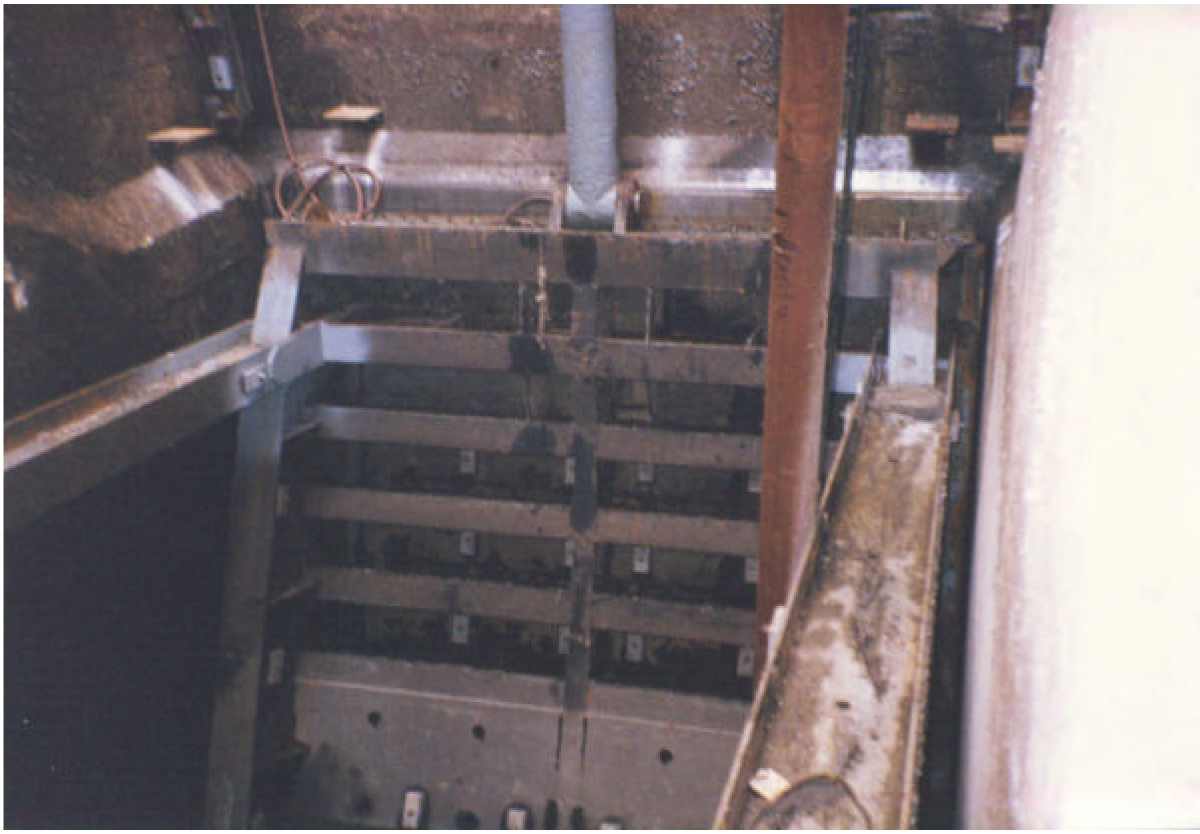


Figure 6.4.2.C. Markland Culvert Valve in the Pit
Note the corrosion of the valve relevant to the spot -painted areas.

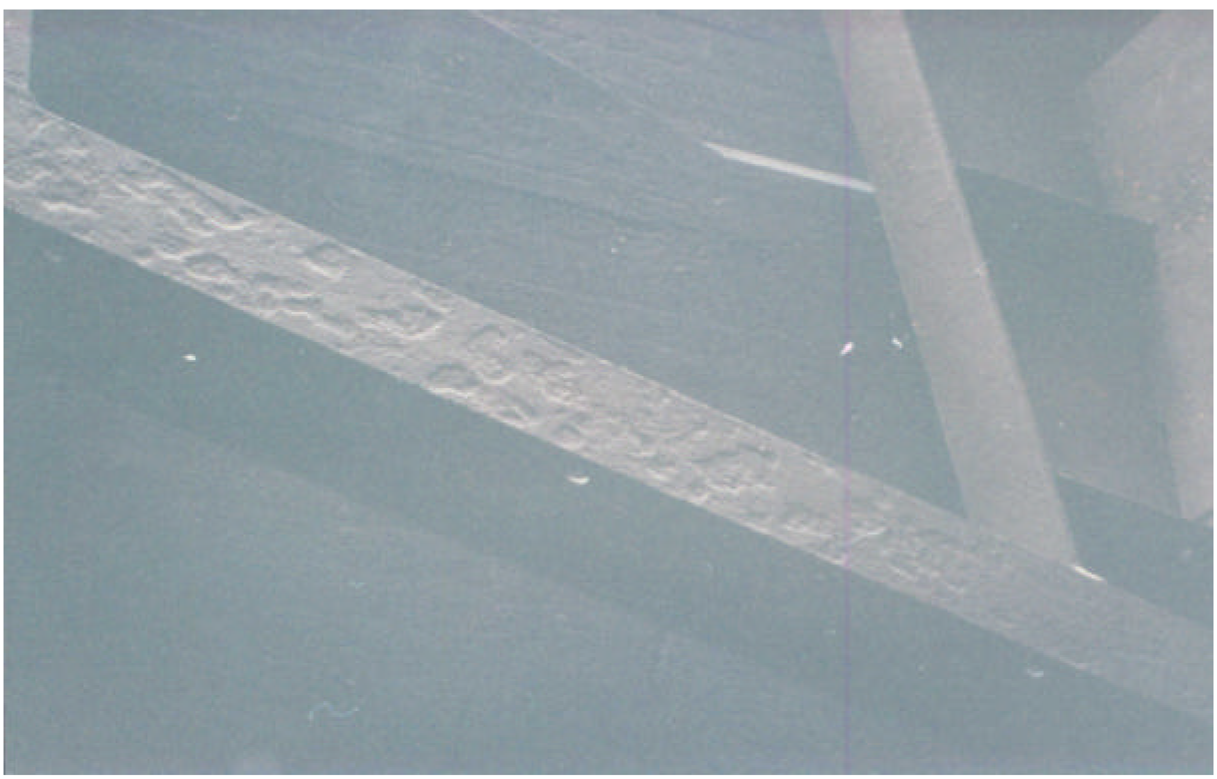


Figure 6.4.2.D. Markland Culvert Valve Strut Arm
Note heavy pitting and corrosion of strut arm.

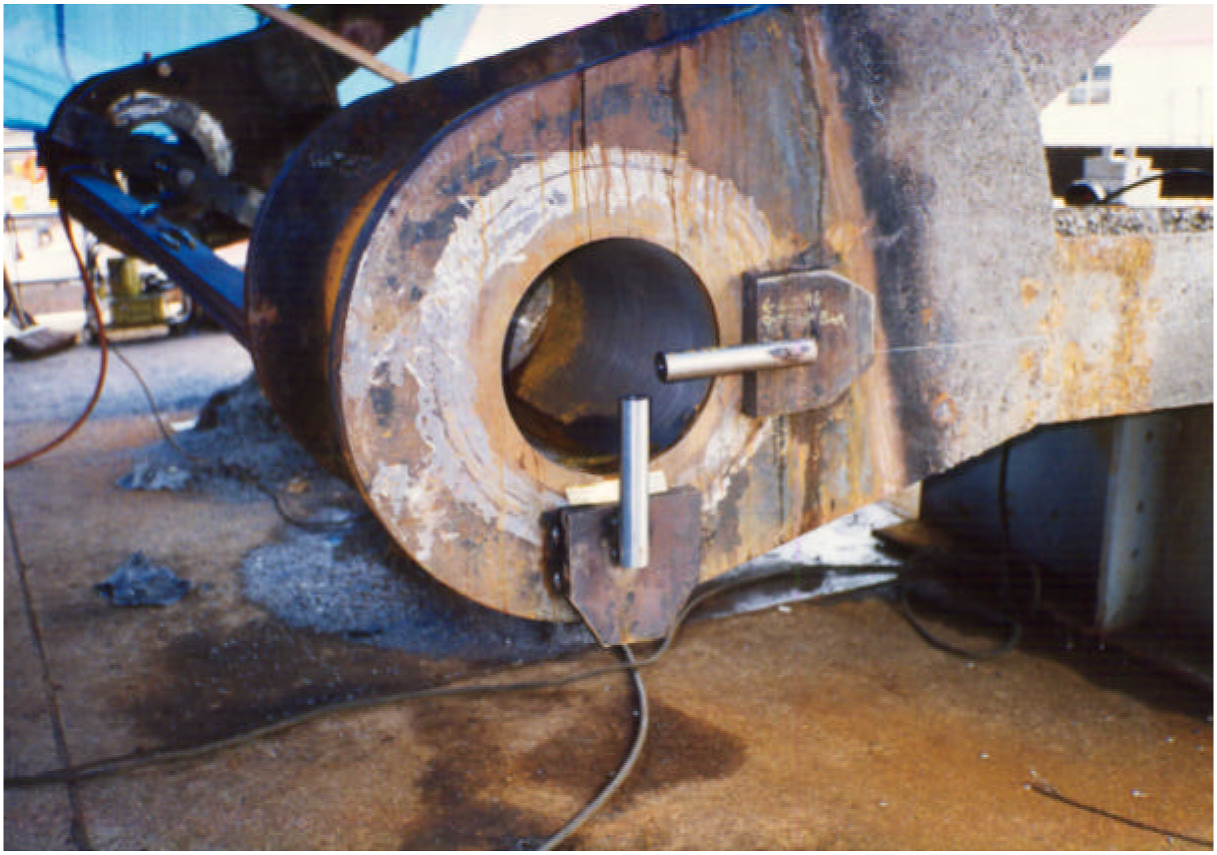


Figure 6.4.2.E. Markland Culvert Valve Bushing
Photograph depicts connection of valve body to pin plate casting.

The first step is to evaluate the stress distributions in a global model of the culvert valve to identify locations where fatigue cracking can lead to reliability problems. A global model of a culvert valve was constructed using half symmetry, and areas of stress concentrations were evaluated for applied operating load conditions. Two areas showing the highest stress concentrations are identified, and refined meshes are incorporated into the global model for these areas. Figure 6.4.3.A illustrates the global modeling for the culvert valve with the mesh refinement at the potential cracking areas. One area is the welded connection for the flange of the vertical load girder attached to the web of the strut arm. The other area for investigation is the welded connection of the strut arm flange to the trunnion pin casting. Global model calculations are conducted using a normal operating head of 30-ft (uniform pressure load) to determine the likely alternating stress ranges for crack initiation at these stress concentration areas. Adjusting for the nominal residual stress of 20 ksi tension at these connections gives alternating stress ranges of about 11 ksi at the girder flange to strut arm web connection and 9.5 ksi for the strut arm flange to trunnion pin block connection. Thus, cracking would initiate first at the girder flange to strut arm web connection. However, by considering the limit state involved at these two connections, it was determined by the engineering team that the strut arm connection to the trunnion pin block is the more critical for reliability.

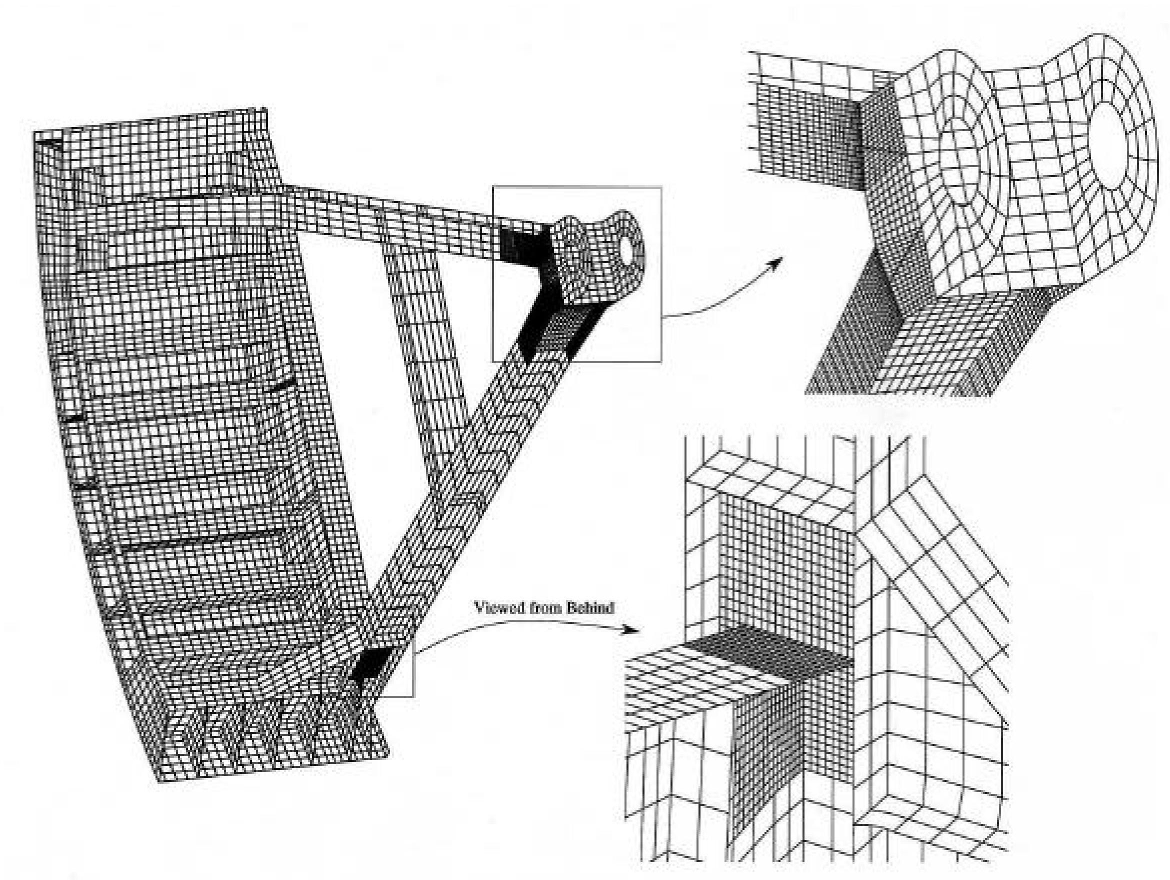


Figure 6.4.3.A Global Finite Element of Markland/Greenup Culvert Valve

The engineering team then established the variables to characterize in the reliability model for fatigue cracking at the strut arm connection to the trunnion pin block. The residual stress at the welded connection is a function of the yield stress. Because of schedules and budget, detailed residual stress calculations of this connection were not employed. However, based on past experience, it is known that tensile residual stresses will develop during the welding of the connection. Since detailed calculations were not performed, a larger random variation is used for the residual stress as a function of yield stress. The operating loads develop tensile stress at this connection that will depend on the operating head and the amount of thickness reduction due to erosion-corrosion. Thus, a matrix of calculations were performed using head variations and thickness reduction of the strut arm flange to determine the maximum principal stress at the connection as a function of head (in feet) and thickness reduction (in inches) as shown in Figure 6.4.3.B. An equation was developed to fit this variation. For crack initiation, it is assumed that the valve open cycle produces a zero peak stress at the connection. The alternating stress is then determined from ½ of the maximum principal stress as a function of the random variables and adjusted for residual mean stress.

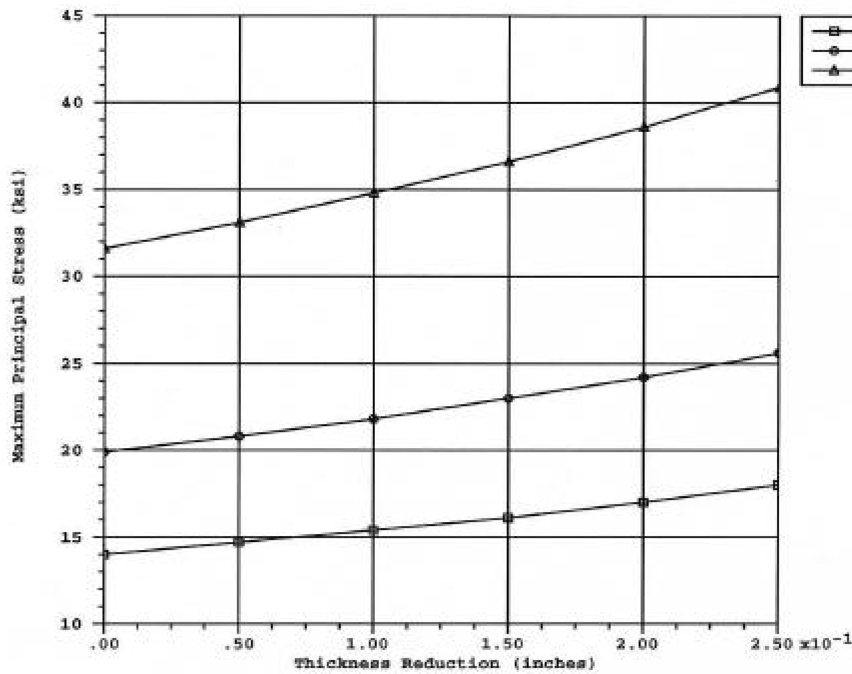


Figure 6.4.3.B Max. Principal Stress Versus Thickness Reduction as a Function of Head

The crack growth rate is now determined by extending a crack at the connection and calculating the stress intensity value versus crack length from the J-integral. Again, detailed residual stress calculations were not performed to establish the residual stress around the welded connection. However, because the crack is extending along the weld line for this case, it is assumed that the residual stress distribution is fairly constant along the path of the crack. Then, since fatigue crack growth is governed by the stress difference over the operating cycle, the residual stress will cancel out in determining the change in stress intensity. The magnitude of residual stress will affect the growth rate and this effect gets included in calculating the exponent on the change in stress intensity in the Paris relation. The fatigue crack growth rate is determined for a reliability model by conducting a matrix of analyses with variations in head and thickness reduction. For each combination, the crack is extended and the stress intensity computed for an open and closed valve condition. The resulting stress intensity versus crack length relation for that combination of variables is used to integrate the Paris relation to obtain number of cycles versus crack length as illustrated in Figure 6.4.3.C. An equation is then developed to fit this data that can return an increment in crack extension for a given increment in the number of cycles on a current crack length.

6.4.4 Limit State for Horizontally-Framed Reverse Tainter Culvert Valves

Once the crack initiation and fatigue crack growth rate are characterized, the limit state of the culvert valve must be established. The limit state is defined as the extent of fatigue cracking that will compromise the structural integrity of the culvert valve. As mentioned in the previous section, the first step was to determine which of the two areas identified for potential fatigue cracking was the more critical for valve integrity under crack growth. To this end, extensive cracks were introduced in the finite element model at the two locations to evaluate the potential consequences. The top flange of the vertical load girder was completely disconnected from the welded attachment to the web of the strut arm. Under operating loads, the stress was redistributed to the web of the vertical load girder. Although stress concentrations were attracted to this new area, excessive deformations or stresses did not develop in the damaged area. This implies that cracking would continue to develop at this location, but that fairly extensive damage may be needed before the structural integrity is compromised. One the other hand, extending a crack in the flange of the strut arm connection to the trunnion pin block caused increased stress concentrations to develop ahead of the crack since a direct reduction of area on a tension member occurs. Thus, fatigue cracking here will undoubtedly progress into a failure of the valve. Therefore, this connection was judged by the engineering team to be more critical and was used to develop a reliability model.

The next step is to determine the extent of cracking that is considered the limit state for the valve. Since this connection is cycled from near zero load to tensile loads, buckling cannot be used to determine a limit state as was done for the miter gate flange connections. Linear elastic fracture mechanics formulas were considered for defining a critical crack length for brittle fracture. However, the size of the connection and the assumed fracture toughness for the material makes this connection very resistant to brittle fracture. Thus, criterion was established for the amount of plastic yielding ahead of the crack to determine the limit state. As the crack extends, the stress concentration increases at the crack tip and the amount of plastic yielding will steadily increase. A criterion was established such that when yielding occurs throughout the thickness of the flange and about ½ the flange thickness in front of the crack, then a limit state is defined. Under these conditions, plastic ductile tearing will likely initiate rather than the fatigue cracking mechanism. The tensile load in the arm will then rapidly propagate the tearing until net section yield results.

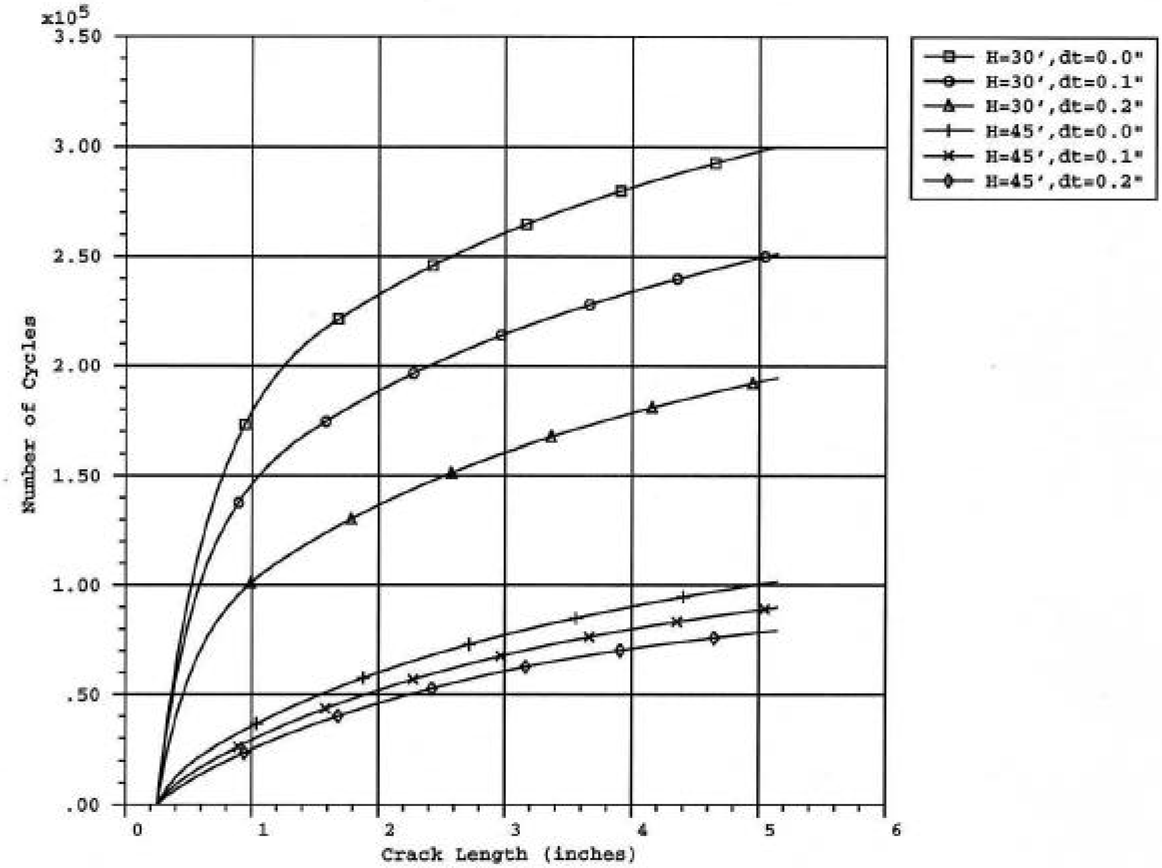


Figure 6.4.3.C. Crack Length vs. Number of Cycles as a Function of Head, Thickness Loss

This criteria means that the critical crack length or limit state is a function of the yield stress, the operating head, and the thickness reduction due to erosion-corrosion. For a given yield stress and operating head, the critical crack size will decrease as the corrosive environment reduces the thickness of the flange. Thus, a matrix of analyses must be performed to find the crack length where the plasticity criteria is reached for variations of the three variables. For each combination of variables, a series of crack lengths are incorporated into the model, and the linear elastic stress distribution at the crack tip is evaluated with stress contour plots, as illustrated in Figure 6.4.4.A. When stresses greater than the yield stress are calculated throughout the flange thickness and for a region ahead of the crack, the corresponding crack length is established as the limit state for that combination of variables. An equation is then developed to relate the critical crack length to yield stress, operating head, and thickness reduction.

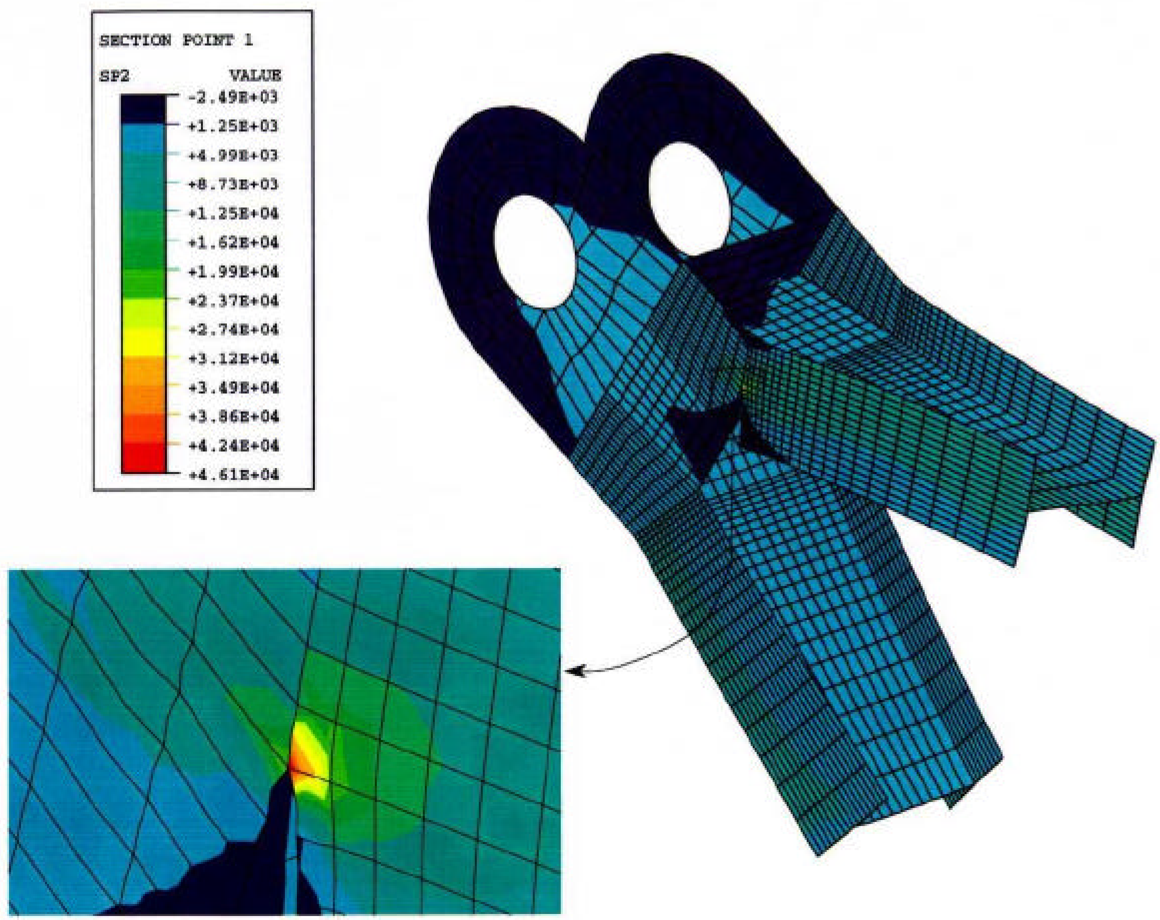


Figure 6.4.4.A Linear Elastic Stress Distribution at Crack Tip

Finally, the influence of the hydrodynamic effects of the water impinging on the valve during the opening cycle must be addressed. This force will increase the loads in the structural components above the hydrostatic pressure head. For design, a "dynamic amplification load" of 1.5 to 2.0 times those due to the hydrostatic pressure is typically used. For the fatigue cracking reliability model, a realistic assessment must be determined in order to take any safety factors out of the analysis. As a method of determining this amplification factor on the operating head, a fluid flow analysis of the valve was conducted. The fluid flow calculation solves the Navier-Stokes equations for pressure gradients and fluid velocities using finite elements for the fluid filled regions. For this analysis, the valve was modeled as a smooth and rigid surface within the fluid flow region. Thus, no structural feedback is included. The fluid velocities and pressures are calculated for various gate open positions. The pressures calculated in the fluid at the gate surface are used to determine the likely factor for gate loads above the hydrostatic head applied in the structural calculations. Figure 6.4.4.B illustrates the geometry, fluid velocities, and fluid pressure contours for this calculation. These calculations indicate a factor of 1.25 on the hydrostatic head is likely for hydrodynamic loads of opening the valve under a 30-ft. head differential.

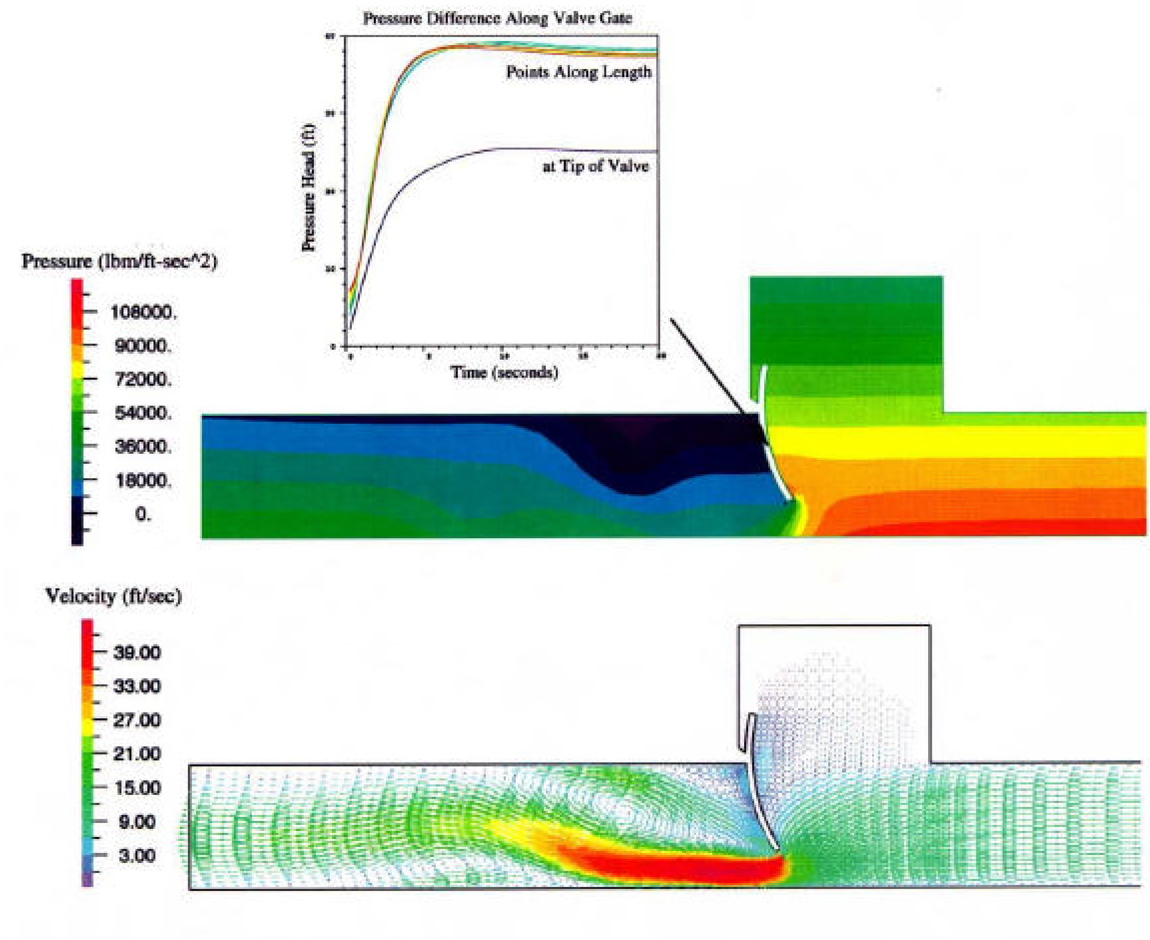


Figure 6.4.4.B Fluid-Structure Interaction Diagrams and Contour Plots

6.4.5 Reliability Model Details

The reliability analysis for the horizontally-framed reverse tainter culvert valves was developed to measure the reliability associated with these type structures. In order to accomplish this effort, the team initially developed a spreadsheet model that investigated the typical analysis of the valves. The spreadsheet analysis included such items as fatigue associated with bending of the horizontal beams that transfer load from the skin plate and also the bending of the main vertical girders. Additionally, axial force in the strut arms was checked over time with regard to fatigue and corrosion. The spreadsheet analysis showed no potential reliability problems with the valves *even after they would have been over 100 years old*. Neither the engineering team nor the operations personnel that work on the valves believed this to be an accurate representation of the reliability of the structure. This was due to the conservatism built into the design at the time of construction. However, it is known from reviewing operations records that repairs to the valves at Markland and other similar designed structures have caused significant chamber closures and costly repairs. Additionally, pitting and corrosion of the valves appears to be considerably greater for valves than other structures because of the turbulent water flowing across the structure associated with the opening and closing of the valve during chamber operation. Therefore, the engineering team decided that it would again be prudent to have a finite element analysis completed for the valves to investigate any potential problem areas. The engineering team decided to develop a Visual Basic coded model specifically for the ORMSS horizontally-framed reverse tainter culvert valves which was modeled after the one developed for the miter gates. The model was named HFCVWELD for horizontally-framed culvert valves. HFCVWELD was developed to investigate the reliability associated with the limit state described in Section 6.4.4.

HFCVWELD Reliability Model

The computer program HFCVWELD has been developed to complete a reliability analysis of the horizontally-framed culvert valves on the Ohio River system. The model was developed to measure the performance of the valves over time. Additionally, the model is used to determine if it is a better decision to replace the valves at some scheduled date as opposed to fixing them after they perform unsatisfactorily.

The basis of the model is that it is a time dependent reliability model for a structure subject to fatigue and corrosion. Therefore, input items such as paint history, corrosion rates, historical operating head with cycle information, and other variables are used in the model to determine the time dependent reliability of the structure.

Using the analysis and limit state information from the finite element modeling, HFCVWELD computes the time dependent reliability of the culvert valves given the input values. A critical crack length is input into the model as the limit state. For each iteration, the model determines the year in which a fatigue-related crack initiates and marks that year. Once the crack initiates, it is allowed to grow relative to the operating cycles within the histogram for each year after the time that it initiates. Once the crack reaches the limit state crack length, the year is tracked, recorded and marked as the year of unsatisfactory performance. This is done for each iteration and the results tabulated in a separate file.

The input menus associated with HFCVWELD look very similar to the ones for the miter gates. Input menus for things such as lock information, crack parameters, loading histograms, traffic cycles, etc. are input similar to the HWELD model for miter gates. In order not to repeat similar figures, please refer to the horizontally-framed miter gate model input narrative in Section 6.2.7 for figures depicting what the input menus look like.

1) <u>Lock Information</u>. The first portion of input is the project name and chamber that is being analyzed. For Markland and Greenup, the valves for both the main and auxiliary chambers are the same in terms of design and construction technique. However, operating cycles and age are different for the chambers and thus, each must be analyzed separately.

2) <u>Crack Parameters</u>. The initial crack length is set to a default value of 0.25 inches, the same as the miter gate initial crack length. The critical crack length is a function of other random variables within the model and thus, is not input separately by the user. It is computed for each individual iteration within the model.

3) <u>Head Histogram</u>. The head histogram reflects the actual past distribution of head differential and hydraulic cycles for the reversed tainter valves. This distribution is based on true daily lockage cycles of each chamber available from the Lock Performance Monitoring

System (LPMS) combined with the true head differential for each day. This distribution is very valuable in determining the fraction of annual cycles versus the expected head differential that can be used for fatigue analysis. The head histograms developed by WES are based on data collected and analyzed for approximately 12 years (1984–1995, inclusive) of lock operation. The HFCVWELD program allows the input of up to 20 different blocks for head (at specified midpoints) and fraction of cycles from the histograms. This histogram is used in HFCVWELD to parse the input annual cycles into the defined stress range blocks and number cycles for fatigue analysis.

4) Traffic Cycles. The number of operating cycles for the gates are determined for each lock based on actual and predicted future cycles for the study period. The cycle information is used in fatigue analysis incorporated into the HFCVWELD program. The cycles are input from the start of operation to the end of the study period. Operating cycles from the origination of the project in 1958 through 1983 were determined by going through the log books at each project to determine the number of lockages in each chamber. From the LPMS data from 1984 through 1995, a ratio of lockages to operating cycles was determined and assumed to be the same in the past as well as for future projected cycles. Traffic cycles for 1984 through 1995 was determined using LPMS data. Finally, projected traffic through the end of the study period was determined by Huntington District's Navigation Center in Huntington, WV. Traffic cycles are the same as for the miter gates.

Random Variables for HFCVWELD

The random variables incorporated into the HFCVWELD analysis are the yield strength of A36 steel, corrosion rate, residual stress factor, and the dynamic amplification factor. The values and ranges for the yield strength are the same as for the miter gates. The corrosion rate selected was for a structure subjected to wet/dry applications because the valves are constantly in and out of the water during operation. This rate is termed in the "splash" zone and has a higher corrosion rate than a submerged structure that was used for the miter gate analysis. Additionally, it was assumed that the valves only had an initial effective paint life of 5 years because of the turbulent water conditions impacting the valve during filling and emptying operations. This was based upon engineering judgment. However, sensitivity analyses were conducted varying the "effective" paint life from 0 to 20 years and it did not turn out to be a controlling variable. Therefore, the five-year life was used. Because a detailed residual stress analysis was not possible for this model due to funding and schedule constraints, a residual stress factor was created to attempt to measure the randomness associated with the residual stress analysis required for this model. The factor was based upon the residual stress analysis completed for the Markland miter gates. Finally, a dynamic amplification factor was needed to measure the increase in load on the valve due to the high velocities that occur during filling and emptying operations. This value (along with appropriate range) was determined by using a fluid flow analysis within the finite element model. This is described in Section 6.4.4. Again, all random variables were selected using Monte Carlo simulation.

1) Yield Strength. The distribution for yield strength is based on data from the published literature and previous Corps of Engineers reliability studies. The distribution is based on a truncated lognormal with a nominal yield stress of 38.88 ksi (i.e., mean yield strength times

the strength ratio) and a standard deviation of 5.44. The lower limit for truncation is based on one standard deviation below the nominal (33.44 ksi) and the upper limit is based on approximately two standard deviations above the nominal (51 ksi). The distribution and statistical moments for yield strength of the steel are the same as used for the miter gates.

2) Corrosion Rate. The distribution for corrosion is based on the data from the published literature and previous Corps of Engineers reliability studies. Corrosion is based on a power law that has been fit to actual field data in various corrosive environments. The equation used for the corrosion is $C(t) = A*t^B$, where A is a random variable based on field measurements, B is generally a constant based on different corrosive environments and C(t) is the corrosion in micromils/yr. For this report, the mean value of A was selected based on submerged corrosion. This distribution used for A was a truncated lognormal with a mean value was 140 and standard deviation of 42. The upper limit of the distribution was taken at 224 and the lower limit at 56. The value for B was a constant of 0.667. These limits and constants are based on actual field measurement of hydraulic steel structures.

3) Residual Stress and Dynamic Amplification Factors. Two types of factors are utilized in HFCVWELD to account the major differences in stress values between traditional hand calculations and the more sophisticated finite element analysis. The residual stress factor is for tensile stresses that are created during the heating and subsequent cooling of the welds at the time of construction. The second factor is the dynamic amplification factor, which represents increased load on the valve that is created by the vortex flow and pressure differential of the water around the valve upon opening. This quick change in pressure increases the stresses on the strut arms during valve operation. An extensive search for field measurement data on this subject was conducted, but did not turn up any definable results for forces on the valve. Therefore, these adjustment were determined based on a fluid flow finite element analysis to determine the range of values that may be exhibited in the valves.

The distribution for the residual stress model factors was considered to be normal since the limits were primarily defined as concentrated about a certain ratio. The mean value for residual stress was 0.35 with a standard deviation of 0.05. The dynamic amplification factor was determined to be a normal distribution with a mean of 1.25 (25% increase) and a standard deviation of 0.025 (2.5%). For further definition, refer to Section 6.4.4.

6.4.6 HFCVWELD Reliability Model Results and Event Trees

The output from the HFCVWELD reliability model is hazard functions giving the overall probability of unsatisfactory performance of the culvert valve over time. For simplicity, it was decided to look only at the reliability associated with a single valve as compared to all four simultaneously for the main chamber. This was done because of the type of failure that is being investigated in the model would cause such concern regarding the condition of the other valves, that the chamber would be shut down at least temporarily for inspection and repair to the remaining three valves. Additionally, the engineering team working on the valves thought the differences between the main chamber and auxiliary chamber could essentially be worked out in the event trees regarding lock chamber closure and repair scenarios.

Main Chamber Hazard Rates and Event Tree

The hazard rate associated with a single culvert valve in the main chamber is very low for Greenup. The main chamber culvert valve probability of unsatisfactory performance initially becomes a non-zero value in the year 2024. The hazard rate reaches 1% in year 2062, and reaches a maximum of 1.3% in 2070. These hazard rates are considerably lower than those that were computed for the culvert valves at Markland, which calibrated well with field experience. The hazard rates for Markland reach 1% in 1990, 5% in 2003, and 10% in 2017. The hazard rate for the Markland main chamber culvert valves reaches a maximum value of approximately 25% in 2065. Refer to Figure 6.4.6.A for a graphical illustration of the reverse tainter culvert valve hazard rates at Markland and Greenup.

There are two major reasons that the Markland culvert valves have higher hazard rates. Remembering that the valves are of the same design, the most important factor affecting the difference in hazard rates is that Markland normally operates at a head of 35 feet, whereas, Greenup generally operates at a head of 30 feet. This causes an increase of 17% in the hydrostatic pressure under normal conditions. Additionally, there have been approximately 16% more operating cycles to date at Markland compared to Greenup. Higher cycles at higher stress levels leads to a higher hazard rate for Markland.

The event tree for the main chamber culvert valves is different than one for the auxiliary chamber. Because the redundancy associated with the set of valves on the main chamber, it is possible to operate the main chamber on only two valves as opposed to four, although the filling and emptying time is roughly doubled over normal operation. However, the doubling of filling and emptying time does not begin to compare to the navigation disbenefits associated with having the main chamber closed and needing to move large tows through the smaller auxiliary chamber. Therefore, it was decided that separate event trees were needed for the two chambers. The event tree for the main chamber is shown in Figure 6.4.6.B. A similar format as used for the miter gate event tree was used for the valves. Assuming an unsatisfactory performance of the culvert valve based upon the mode selected in the reliability model, three possible repair scenarios were chosen. A breakdown of these repair scenarios, along with their costs and closures are provided below.

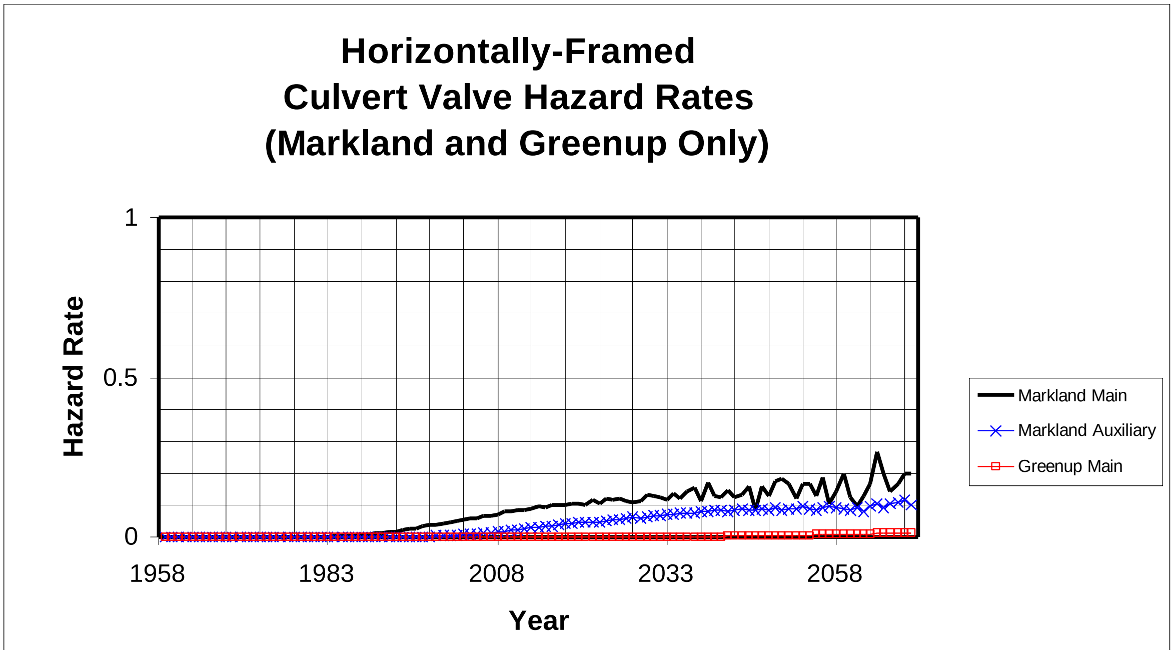


Figure 6.4.6.A. Markland and Greenup Culvert Valve Hazard Rates

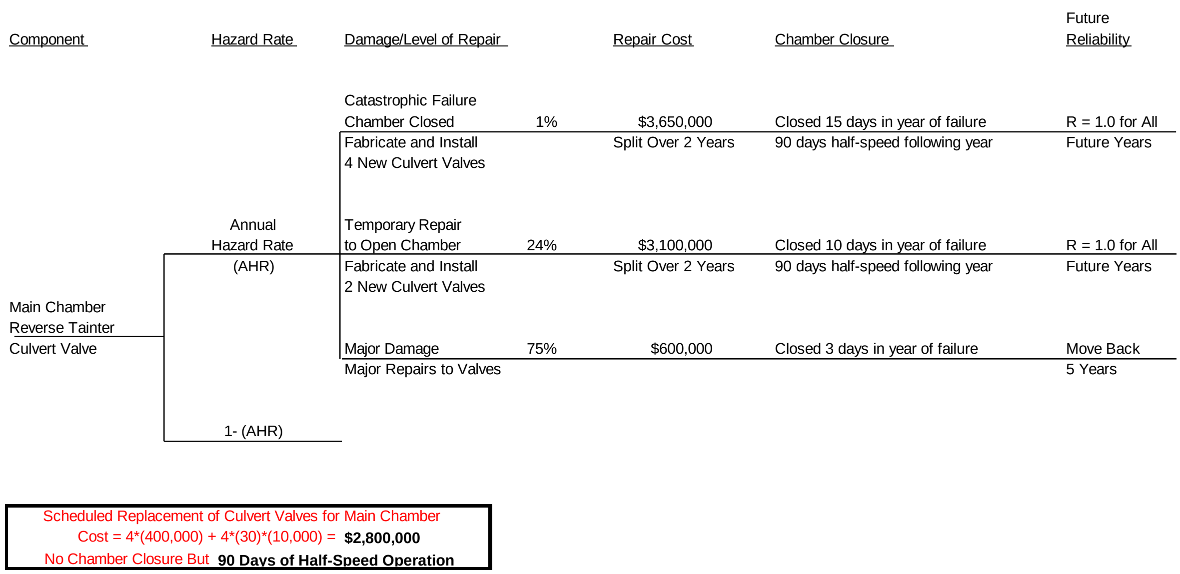


Figure 6.4.6.B. Main Chamber Reverse Tainter Valve Event Tree

<u>Catastrophic Failure, Install 4 New Valves.</u> This repair assumes the worst situation, a catastrophic failure of a culvert valve. It is assumed the damage and potential problems associated with it are enough to warrant a significant closure of the main chamber. Because the main chamber could be put back in service with only 2 valves, the repair scenario assumes that the chamber would not be opened again until temporary repairs can be completed on two of the valves. The closure in the year of the failure is assumed to be 15 days to complete inspections and

emergency repairs to the other filling and emptying valves. It is assumed that 30 additional days are required to make extensive, temporary repairs to the failed valve. The following year 4 new valves would be installed in a manner such that the chamber is never closed, but operates at half-speed filling and emptying times for 90 days. Future reliability is assumed to be equal to1.0 for the remainder of the study since new valves are installed. The repair cost associated with this repair is $3,650,000. This amount is split over two years. A breakdown of the costs is supplied below.

Year of failure, assumes emergency conditions	
Repair fleet on site 45 days at $10,000 per day →	$ 450,000
Emergency fabrication of 4 new valves (4 at $500,000 each) →	$2,000,000
Following year, install 4 new valves	
Repair fleet on site 120 days at $10,000 per day →	$1,200,000
Total for Catastrophic Repair Cost →	$3,650,000

It is assumed that the chance of a catastrophic failure of this magnitude is quite low, therefore, it was decided to only place about a 1% chance of this occurrence on this branch. Additionally, the cost of fabricating the valves is increased by 25% for the assumption all work would occur under emergency conditions.

Temporary Repair with New Valves Following Year. This repair assumes that the major damage has occurred to one of the four valves. The chamber is assumed closed for 10 days. This includes time for the repair fleet to organize and get to the site. This could be several days under the best circumstances. The remaining time is for the inspection and repair to at least two of the valves to open the chamber. An additional 20 days is required for the emergency repair to the other two valves. Then 4 new valves are fabricated and delivered to the site in the following year for installation. Installation is assumed to take 120 days, with about 90 days having the chamber at ½ filling and emptying speed. The repair cost for this alternative is estimated to be $3,100,000 with chamber closure time of 10 days. There is an additional 90 days of the main chamber operating at half speed. Future reliability is assumed to be equal to 1.0 for the remainder of the study since new valves are installed the following year. A breakdown of the costs for this repair is supplied below.

Year of failure, assumes emergency conditions	
Repair fleet on site 30 days at $10,000 per day →	$ 300,000
Following year, install 4 new valves	
Emergency fabrication of 4 new valves (4 at $400,000 each) →	$1,600,000
Repair fleet on site 120 days at $10,000 per day →	$1,200,000
Total for Temporary Repair with New Valves →	$3,100,000

It was agreed that this scenario represented a reasonable chance of occurring regarding repair technique, thus, 24% was placed on this branch. It is believed that the repair fleet would do everything possible to get the chamber operational again, however, major damage would prompt the district to obtain the funds to procure new valves.

Major Repair, Leave Existing Valves. This repair assumes the least damage to the culvert valves, such that they are repairable and can continue in service. For this situation, the main chamber is assumed to be closed for 3 days for inspection and repair to the culvert valves. However, it is assumed the repair fleet will be on-site for a total of 60 days for extensive repairs to all four valves to extend their serviceable lives. The cost associated with this alternative is $600,000. Almost all of the repair time would be with the main chamber operating at half-speed. Since the existing valves are left in place, it is assumed the repair would only improve the reliability of the structure by an "effective" five years. Therefore, the updated reliability in the following year resets to the value it was 5 years before the failure. Again, this was the easiest way to reset hazard rates in the economic model. A breakdown of costs associated with this repair is provided below.

Year of failure

Repair fleet on-site for 60 days at $10,000 per day → $600,000

The $600,000 cost reflects the total for this scenario. Along with operations review, it was decided that this repair scenario represents the most likely solution. Therefore, the remaining 75% was applied to this branch.

<u>Scheduled Replacement of Culvert Valves</u>. The other piece of information the economists need is the cost and chamber closure or filling/emptying effect associated with the scheduled replacement of the valves before failure. There are four valves for the main chamber and it can be operated at half-speed in the event of repair or replacement work to one of the valves. The cost and closure breakdown associated with a scheduled replacement of the main chamber culvert valves is provided below.

Year of scheduled replacement

Fabrication and delivery of 4 valves ($400,000 each) →	$1,600,000
Repair fleet time (4 valves x 30 days each x $10,000 per day) →	<u>$1,200,000</u>
Total cost to replace all 4 valves of main chamber →	$2,800,000

Auxiliary Chamber Hazard Rates and Event Tree

The hazard rate associated with a single culvert valve in the auxiliary chamber at Markland is graphically in Figure 6.4.6.A. The main chamber culvert valve hazard rates for Markland and Greenup are also shown on this graph for comparison to the Markland auxiliary chamber. As shown in the figure, the Markland auxiliary chamber culvert valve probability of unsatisfactory performance initially becomes a non-zero value in the year 1981. The hazard rate does not reach 1% until the year 2006. Values reach 5% and 10% in years 2024 and 2057, respectively. The Greenup auxiliary chamber culvert valves were analyzed, however, the probability of unsatisfactory performance for the chosen limit state was determined to be insignificant throughout the study period. This does not indicate that there will never be necessary repairs to the Greenup auxiliary chamber valves. The assumption is made that repairs are made during scheduled chamber dewaterings to handle any operational problems associated with the auxiliary chamber valves and the fatigue action associated with the limit state is not expected to occur on the Greenup auxiliary chamber valves.

The hazard rate associated with the Markland auxiliary chamber culvert valves is considerably lower than the Markland main chamber, strictly a function of operating cycles over time. However, there is no redundancy associated with the valves for the auxiliary chamber and any work on them, either repair or replacement, closes the chamber to navigation traffic, i.e. no half-speed capability for the auxiliary chamber. This is accounted for in the event tree for the auxiliary chamber culvert valves and the economic analysis.

The event tree for the auxiliary chamber culvert valves is shown in Figure 6.4.6.C. The format is similar to the event tree for the main chamber culvert valves. The same three repair levels are used in the auxiliary event tree, however, the costs and consequences are different than the main chamber for two reasons. They are the fact that there are only two valves for the auxiliary chamber (as compared to four for the main chamber) and the auxiliary chamber can not operate at ½ filling and emptying speed. A breakdown of each of the repairs is provided.

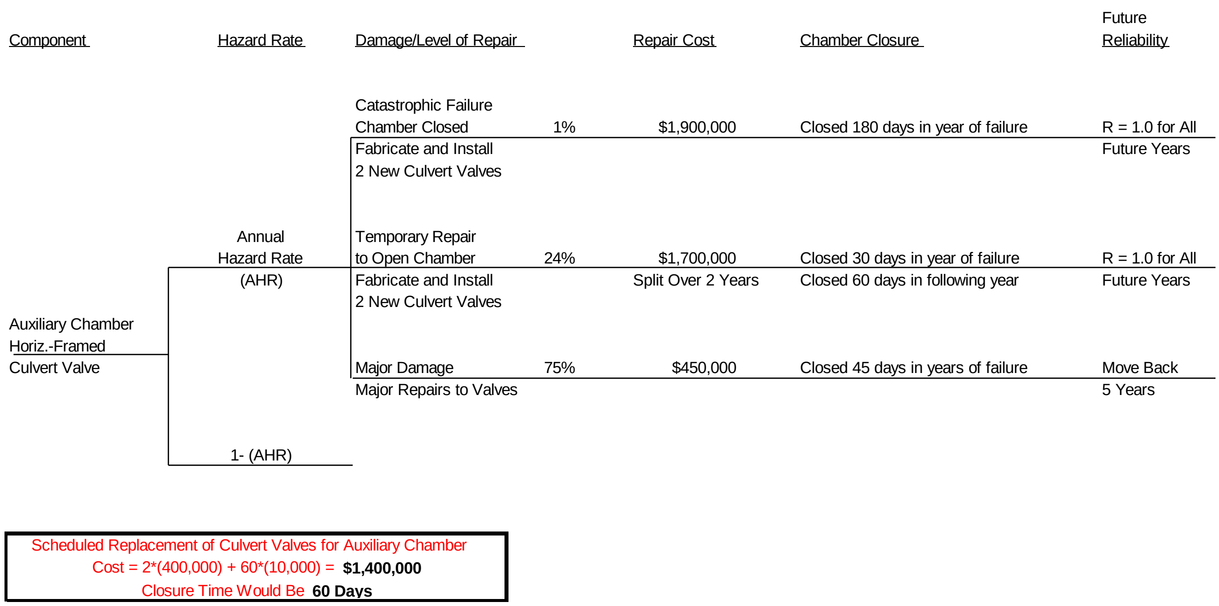


Figure 6.4.6.C. Auxiliary Chamber Event Tree for Horizontally-Framed Reverse Tainter Culvert Valves

Catastrophic Failure, Install 2 New Valves. This repair assumes the worst situation, a catastrophic failure of a culvert valve. It is assumed the damage and potential problems associated with it are enough to warrant a lengthy closure of the auxiliary chamber. It is assumed that the valve is no longer operable and must be replaced. This repair also assumes the immediate fabrication of two new valves after failure. The 180 days incorporates the time to pull out the failed valves, fabricate, and install two new valves. The length of the closure is associated with the time to fabricate and deliver the valves since spares are not available. Future reliability is assumed to be equal to 1.0 for the remainder of the study since new valves are installed. The repair cost associated with this repair is estimated at $1,900,000. A breakdown of the costs is supplied below.

Year of failure, assumes emergency conditions

Repair fleet on site 90 days at $10,000 per day →	$ 900,000

Emergency fabrication of 2 new valves (2 at $500,000 each) →	$1,000,000
Total for Catastrophic Failure Repair →	$1,900,000

It is assumed that the chance of a catastrophic failure of this magnitude is quite low, therefore, it was decided to only place about a 1% chance of this occurrence on this branch. Additionally, the cost of fabricating the valves is increased by 25% for the assumption all work would occur under emergency conditions.

<u>Temporary Repair with New Valves Following Year.</u> This repair assumes that the major damage has occurred to one of the two valves. The chamber is assumed closed for 30 days in the year of the failure. This includes time for the repair fleet to organize and get to the site. This could be several days under the best circumstances. The remaining time is for the inspection and repair to both of the valves. Then two new valves are fabricated and delivered to the site in the following year for installation. Installation is assumed to take 60 days to pull out the old valves and install the new ones. The repair cost for this alternative is estimated to be $1,700,000 spread over two years. Future reliability is assumed to be equal to 1.0 for the remainder of the study since new valves are installed the following year. A breakdown of the costs for this repair is supplied below.

Year of failure, assumes emergency conditions	
Repair fleet on site 30 days at $10,000 per day →	$ 300,000
Following year, install 4 new valves	
Emergency fabrication of 2 new valves (2 at $400,000 each) →	$ 800,000
Repair fleet on site 60 days at $10,000 per day →	$ 600,000
Total for Temporary Repair with New Valves →	$1,700,000

It was agreed that this scenario represented a reasonable chance of occurring regarding repair technique, thus, 24% was placed on this branch. It is believed that the repair fleet would do everything possible to get the chamber operational again, however, major damage would prompt the district to obtain the funds to procure new valves.

<u>Major Repair, Leave Existing Valves</u>. This repair assumes the least damage to the culvert valves, such that they are repairable and can continue in service. For this situation, the main chamber is assumed to be closed for 45 days for inspection and repair to both culvert valves. The cost associated with this alternative is $450,000. Since the existing valves are left in place, it is assumed the repair would only improve the reliability of the structure by an "effective" five years. Therefore, the updated reliability in the following year resets to the value it was 5 years before the failure. A breakdown of costs is provided below.

Year of failure	
Repair fleet on-site for 45 days at $10,000 per day →	$450,000

The $450,000 cost reflects the total for this scenario since the existing valves remain in place. It was decided that this and the previous repair scenario represent the most likely solution. Therefore, the remaining 75% was applied to this branch.

<u>Scheduled Replacement of Culvert Valves</u>. There are only two valves in the auxiliary and it can not be operated at half-speed during repair or replacement work to the valves. The cost and

closure breakdown associated with a scheduled replacement of the auxiliary chamber culvert valves is provided below. This replacement scenario assumes the auxiliary chamber will be closed for 60 days.

Year of scheduled replacement

Fabrication and delivery of 2 valves ($400,000 each) →	$ 800,000
Repair fleet time (2 valves x 30 days each x $10,000 per day) →	$ 600,000
Total cost to replace both valves of auxiliary chamber →	$1,400,000

6.4.7 Economic Results for Horizontally-Framed Culvert Valves

Using the culvert valve hazard rates for each chamber and the chamber specific event trees, it can be determined if it is economically justified to replace the culvert valves prior to failure. The economists use the data provided by the engineering team to determine average annual costs associated for the fix-as-fails approach. Additionally, the economists determine the average annual costs for replacing the valves in different years ahead of failure. The option with the lowest average annual cost sets the timed replacement of the valves. Table 6.4.7.A summarizes the average annual costs associated with the culvert valves for both the main and auxiliary chambers at Greenup and Markland. As evidenced by the values in the table, the fix-as-fails option is the most economical solution for the main chamber culvert valves at Greenup. Since there are no failures associated with the auxiliary chamber culvert valves at Greenup, fix-as-fails is the most economical solution for the auxiliary chamber as well. Again, this is not a reflection of the future maintenance required for the valves, it is just assumed that any repairs are made during routine maintenance.

Table 6.4.7.A. Economic Results for Greenup/Markland Culvert Valves

Economic Analysis of HF Reverse Tainter Culvert Valves			
Description of Option	Project	Chamber	Average Annual Cost
Fix-as-Fails	**Greenup**	**Main**	**$26,900**
Replace in 2000	Greenup	Main	$439,700
Replace in 2010	Greenup	Main	$227,100
Replace in 2020	Greenup	Main	$121,200
Replace in 2030	Greenup	Main	$64,600
Replace in 2040	Greenup	Main	$36,500
Fix-as-Fails	Markland	Main	$608,900
Replace in 2000	Markland	Main	$420,500
Replace in 2002	Markland	Main	$396,900
Replace in 2005	**Markland**	**Main**	**$378,900**
Replace in 2007	Markland	Main	$380,000
Replace in 2009	Markland	Main	$388,300
Fix-as-Fails	Markland	Aux	$109,600
Replace in 2000	Markland	Aux	$254,000
Replace in 2010	Markland	Aux	$149,700
Replace in 2020	Markland	Aux	$109,300
Replace in 2030	**Markland**	**Aux**	**$103,900**
Replace in 2040	Markland	Aux	$135,000

The results in the table indicate that the culvert valves at Markland are optimally timed for replacement in 2005 for the main chamber and 2030 for the auxiliary chamber. Adversely, the main and auxiliary chamber culvert valves at Greenup are not justified individually for replacement.

Individual replacment costs and closures for the Markland culvert valves typically would be placed into the cost and closure matrices in the appropriate year. These years would be 2005 for the main chamber and 2030 for the auxiliary chamber. However, in reviewing the required replacement closure for the Markland main chamber, it is noted that the miter gates are also justified for replacment early in the study period (the year 2000). See section 6.2 for the horizontally-framed miter gate narrative for further details. A subsequent economic analysis was completed to determine the optimum time of replacements if both the valve and miter gate replacements could be combined in a more efficient manner. The analysis indicated that completing the replacements of both the main chamber miter gates and culvert valves is optimally timed for the years 2001 and 2002. Consecutive 45 day closures have been input into the cost and closure matrices for the Markland main chamber.

The same type of economic analysis was undertaken to determine the optimum time to replace both the miter gates and culvert valves for the auxiliary chamber. Individually, the auxiliary chamber miter gates at Markland are optimally timed for replacement in 2022, while the culvert valves are most economically justified in 2030. Combining the closures and replacment costs in a more efficient manner indicates that the optimum time to combine the replacements of the valves and miter gates is 2025 and 2026. Therefore, consecutive 45 day closures have been input into the cost and closure matrices for the Markland auxiliary chamber in 2025 and 2026.

6.5 VERTICALLY-FRAMED REVERSE TAINTER CULVERT VALVE RELIABILITY

Reverse tainter culvert valves at Ohio River projects are used to control the filling and emptying of lock chambers. All sites with the exception of the upper three (Emsworth, Dashields, and Montgomery Locks and Dams) utilize reverse tainter culvert valves for the filling and emptying of the lock chamber. Emsworth, Dashields, and Montgomery (EDM) utilize butterfly valves for the operation of their filling and emptying systems. Butterfly valves are covered within the overall mechanical model. There are two types of reverse tainter culvert valves: horizontally-framed and vertically-framed. Separate reliability models had to be developed for each of these reverse tainter culvert valves.

Most Ohio River projects use vertically-framed reverse tainter culvert valves, however, there are several sites with horizontally-framed valves. In general, the older sites use horizontally-framed culvert valves. These include the valves at Pike Island, New Cumberland, Greenup, Meldahl, Markland, and the existing main chamber at McAlpine. The newer projects have vertically-framed valves. These sites include Willow Island, Belleville, Racine, Hannibal, R.C. Byrd, Cannelton, Newburgh, J.T. Myers, Smithland, and Olmsted. This section will focus on the horizontally-framed culvert valves. Section 6.4 focuses on horizontally-framed culvert valve reliability.

Due to schedule and funding constraints, only the vertically-framed culvert valves for J.T. Myers was totally completed (runs calibrated, through ITR, etc.) at the time of this interim report. Therefore, this section will only detail the results for both chambers at J.T. Myers. The reliability assessments of the vertically-framed valves at the remaining Ohio River projects will be completed as part of the overall ORMSS final report. The reliability results for the valves at J.T. Myers will be carried forward into the final ORMSS report.

The vertically-framed reverse tainter culvert valves at J.T. Myers have been in operation since the lock commenced operations in the early 1970's. The design and construction technique for both the main and auxiliary chamber valves are the same, therefore, the same reliability model can be used for each chamber with chamber specific input for historical painting and operating cycles. It is important to note that the significance of an unsatisfactory performance of a reverse tainter culvert valve is quite different depending upon whether it occurs in the main or auxiliary chamber.

6.5.1 Main Chamber Versus Auxiliary Chamber

The main chamber at J.T. Myers has a total of four vertically-framed reverse tainter culvert valves for filling and emptying the lock, two filling and two emptying valves. One filling and emptying valve is in the middle wall and the other set is in the river wall. They can be operated independently. Therefore, a repair to one of the main chamber culvert valves does not necessarily close the chamber. It is possible to dewater the area around the valve only, thus, leaving the other filling and emptying set to operate the chamber. Filling and emptying time is roughly doubled over normal operation. Normal filling and emptying time for J. T. Myers is approximately 8 minutes each.

For the auxiliary chamber, there are two valves to control filling and emptying operations. One filling and emptying valve each. Therefore, a problem with one of the valves on the auxiliary chamber closes the entire chamber while necessary repairs are made. The significance of closing the auxiliary chamber is considerably less than the main chamber where disbenefits associated with the closure can become large for extended closures.

6.5.2 Grouping of Vertically-Framed Reverse Tainter Culvert Valves

The valves are termed vertically-framed since the main load from the skin plate is transferred to large horizontal plate girders by a series of vertical curved ribs. The large horizontal plate girders transfer the load to a series of axially-loaded strut arms that connect the body of the valve to a pin plate casting, which transfers the load to the valve's trunnion beam. The trunnion beam then transfers the load to the concrete monolith. The valves act in tension since the tainter gate is reversed to the direction of flow.

There are nine projects on the Ohio River system that utilize vertically-framed culvert valves. These valves can be broken into four separate groups. The groups are classified as follows:

Group 1. Group 1 vertically-framed culvert valves include those found at Willow Island, Belleville, Racine, and Hannibal Lock and Dams. These valves typically have curved vertical ribs that are approximately 11" deep and ½" thick. The flanges are roughly 6" wide and 1" thick. Most of the horizontal plate girders are 13 ½" deep by 1 ½" thick with flanges that measure 12" wide by 1 ¼" thick. Additionally, all four normally operate at a head of 20 to 22 feet.

Group 2. Sites considered for group 2 are Cannelton, Newburgh, and **J.T. Myers**. Each of these have vertical curved ribs that measure approximately 8" deep by ½" thick. The flanges typically measure 8" x 1". The horizontal girders measure approximately 28" deep by 5/8" thick. All these were built in the early 1970's.

Group 3. The valves at Smithland are the only ones in this group. This is mainly due to the small flange size on the vertical curved ribs. These ribs have flanges that measure only 4" wide by 1 ¼" thick. It should be noted that there was a major failure of one of the Smithland valves in 1998 at the connection of the vertical curved rib and lower horizontal girder. At the time of the failure, the other valves at Smithland were inspected and found to have the same deteriorated condition, thus, on the verge of failure.

Group 4. R.C. Byrd represents the only site with valves in this group. This is because the valves are the newest ones on the Ohio River system (1993) and do not fit well within other categories for member sizes.

Since all the vertically-framed valves on the Ohio River system are similar in construction type and operation, it was decided to develop the reliability model based upon field experience at Smithland Lock and Dam. Therefore, global and local finite element models for the Smithland culvert valves were made in order to develop a time dependent reliability model for all Ohio River Mainstem Systems Study (ORMSS) vertically-framed valves. Therefore, the limit state of the vertically-framed valves was centered around the type of failure that occurred at Smithland. From the Smithland global and local finite element models, appropriate adjustments were made to determine group specific load factors for such things as stress concentration factors associated with different member sizes.

Figure 6.5.2.A shows the vertically-framed reverse tainter culvert valves being painted outside the chamber at Smithland. Note that all of the vertically-framed culvert valves (including those at **J.T. Myers**) are of similar general design and construction technique, thus, setting up the reliability model based upon experiences at Smithland is valid. Figures 6.5.2.B through 6.5.2.F depict the damage at Smithland from the 1998 failure and the limit state selected for the valves.

6.5.3 Finite Element Modeling and Calibration of Vertically-Framed Reverse Tainter Culvert Valves

Finite element modeling is used to develop reliability models for fatigue cracking at welded connections for vertically-framed culvert valves of the type used at the J. T. Myers Locks. This modeling is based on analyses and experience gained from reliability modeling for fatigue cracking at welded connections on miter gates and horizontally-framed culvert valves. In addition, recent field experience involving welded connection failures on a vertically framed culvert valve at Smithland Lock is used to guide the analysis and benchmark the reliability model. On one of these culvert valves, the weld attaching a vertical rib to the main horizontal load beam failed, which separated the rib from the load beam. As the load transferred to adjacent connections, subsequent connections failed, both at the welded connections and from complete fracture through the vertical ribs.

This sequential failure at these connections is diagnosed to have progressed in a fairly rapid manner relative to a reliability study for fatigue cracking. Thus, once a crack initiated at the first welded connection, the operational failure of the valve developed within a relatively few additional cycles of operation. Therefore, for this reliability modeling, the limit state can be considered the initiation of fatigue cracking at the critical connection of the vertical rib to the horizontal load beam, and the finite element modeling concentrated on characterizing the fatigue failure of this connection.

Figure 6.5.2.A. Photograph of Smithland Culvert Valve Being Painted

Figure 6.5.2.B. Side View of Failed Smithland Valve

Note sheared rib at strut arm and offset of curved ribs above and below horizontal girder .

Figure 6.5.2.C. Side View of Failed Curved Rib s at Bottom Horizontal Girder
Note the failure of the weld at horizontal girder in 2nd rib from end. Same weld failure occurred at 2nd rib from other end as well. All other ribs failed in shear.

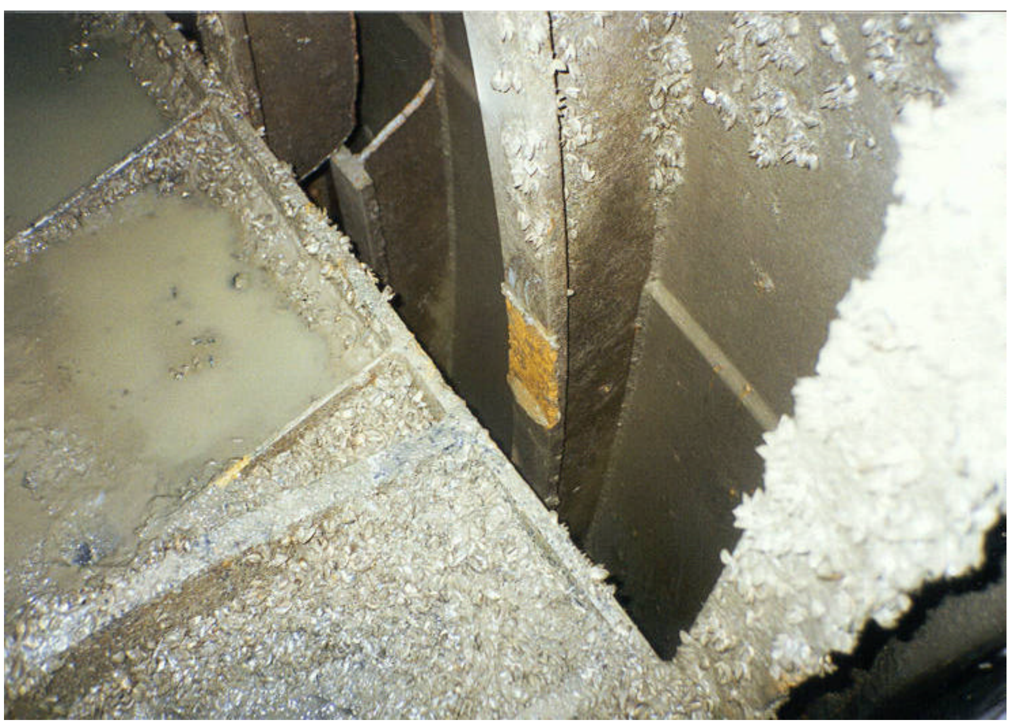


Figure 6.5.2.D. Failure of Weld at 2nd Vertical Rib
Note weld material left on rib after it separated from horizontal girder.

Figure 6.5.2.E. Shear Failure of Vertical Ribs in Middle of Valve
Note vertical rib on far right where initial weld failed.

Figure 6.5.2.F. Shear Failure and End Vertica l Rib

A global model of half of the Smithland lock culvert valve, as illustrated in Figure 6.5.3.A, was developed to identify the local areas that are more susceptible to cracking due to elevated stress concentration factors. The Smithland design was used as a surrogate for the finite element modeling since field data was available for benchmarking and calibrating the reliability model. The global model indicated that the connection between the vertical rib and the horizontal load beam near the edge of the valve would develop the highest stress concentration under the normal operating head. This is the connection that was determined to have failed first in the Smithland culvert valve. More detailed modeling of this connection was then implemented into the global model, as illustrated in Figure 6.5.3.B, to characterize the fatigue cracking at this connection. At this type of connection, the top of the flange plate of the vertical rib is welded directly to the bottom of the flange plate on the horizontal load beam using a fillet weld around the perimeter of the contacting plate areas. In the detailed modeling, the plate elements are constructed along the centerlines of the respective flanges. The two flanges are then connected together with plate elements around the perimeter representing the weld. The thickness of these weld elements is taken as the ligament thickness across the throat of the weld. The membrane stress in these weld elements, which acts through the depth of the weld, is used to establish the stress level for the fatigue cracking evaluations. Figure 6.5.3.B also illustrates the maximum principal stress distribution in the weld at this connection due to the nominal operating head on the valve.

As in the reliability modeling for the horizontally framed culvert valves, a tensile residual stress is assumed to exist in the welded area. Because the connection failure is due to cracking along the weld, the residual stress can be assumed to be constant during the extension of the crack. This is consistent with the field evidence that the fatigue crack extends relatively fast once it initiates. However, since limited funding and time constraints did not allow for detailed modeling of the distribution of residual stresses, a larger variation for the level of residual stress is also assumed in the reliability calculations. The stress level calculated at the connection under the operational loads becomes the stress range for the fatigue cracking since these operational loads are imposed on top of the residual stresses. However, because the stress is cycling about a mean tensile value due to the residual stress, the effective alternating stress for determining the allowable fatigue cycles is adjusted using the Goodman relation.

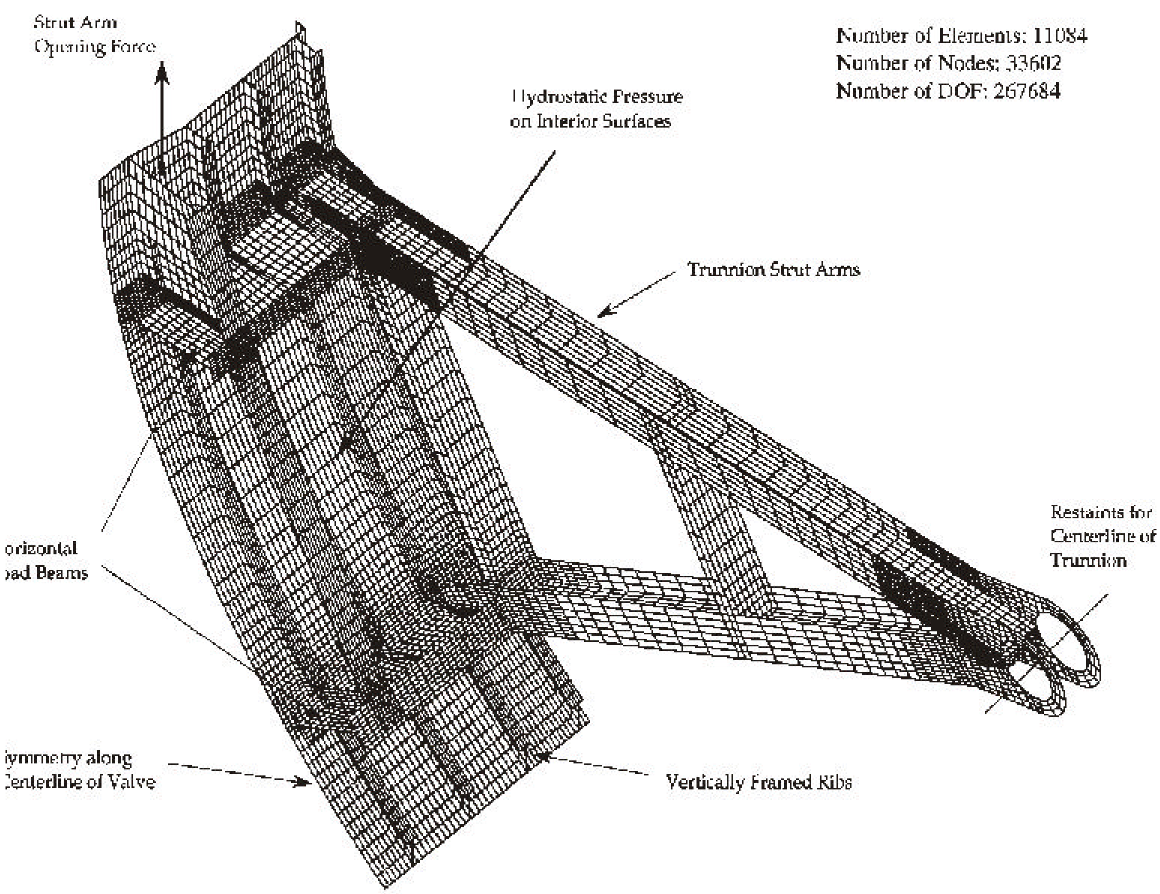


Figure 6.5.3.A. Global Finite Element Model of Smithland Culvert Valve

The calculated peak membrane stress in the welded connection is used to establish a stress concentration factor that can be applied to the design based calculation for the average stress in the weld. The flange sizes are adjusted in the global model to account for the differences in the Smithland and J. T. Myers culvert valve designs. Figure 6.5.3.C shows the principal stress contours for the geometry of the J. T. Myers culvert valve to illustrate the stress concentrations present through the depth of the weld material. The stress concentration is then characterized for variations in operating head and thickness reduction due to corrosion.

The dynamic amplification factor of 1.3 on the nominal pressure head is also used to account for the hydrodynamic loading during opening of the valve. This factor was developed based on fluid flow modeling for a horizontally-framed culvert valve. Since this effect is a function of the general shape of the valve and culvert, rather than the details of the construction, this factor is also used for the vertically-framed culvert valve reliability model. For further details regarding the fluid-flow interaction, please refer to the horizontally-framed culvert valve narrative in section 6.4. Figure 6.5.3.D illustrates the principal stress for crack initiation characterized as a function of head and thickness reduction developed for the reliability model.

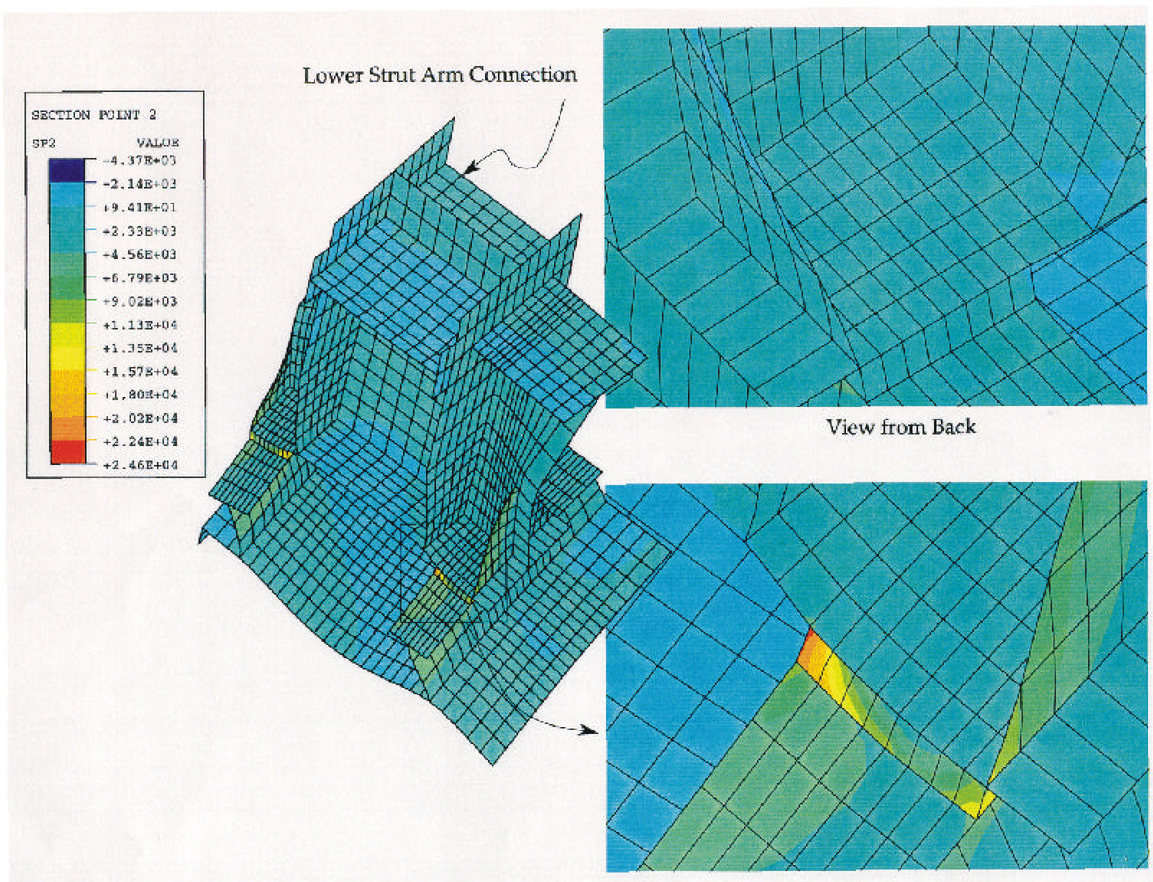


Figure 6.5.3.B. Maximum Principal Membrane Stress Refined Modeling of Welded Connection

As mentioned previously, the limit state of the vertically-framed culvert valve is defined to be the initiation of fatigue cracking at the welded connection between the vertical rib and the horizontal load beam. Field experience indicates that this cracking will rapidly propagate due to the reduction in area resisting the cyclic tensile loads. The cracking will completely separate the vertical rib from the horizontal load beam. As the load is transferred to the adjacent connections, similar failures will propagate until the valve has an operational failure. The failure hazard due to this limit state was benchmarked successfully with the Smithland field experience. Thus, for this reliability modeling, the initiation of fatigue cracking at the first connection is considered sufficient to establish a failure of the valve.

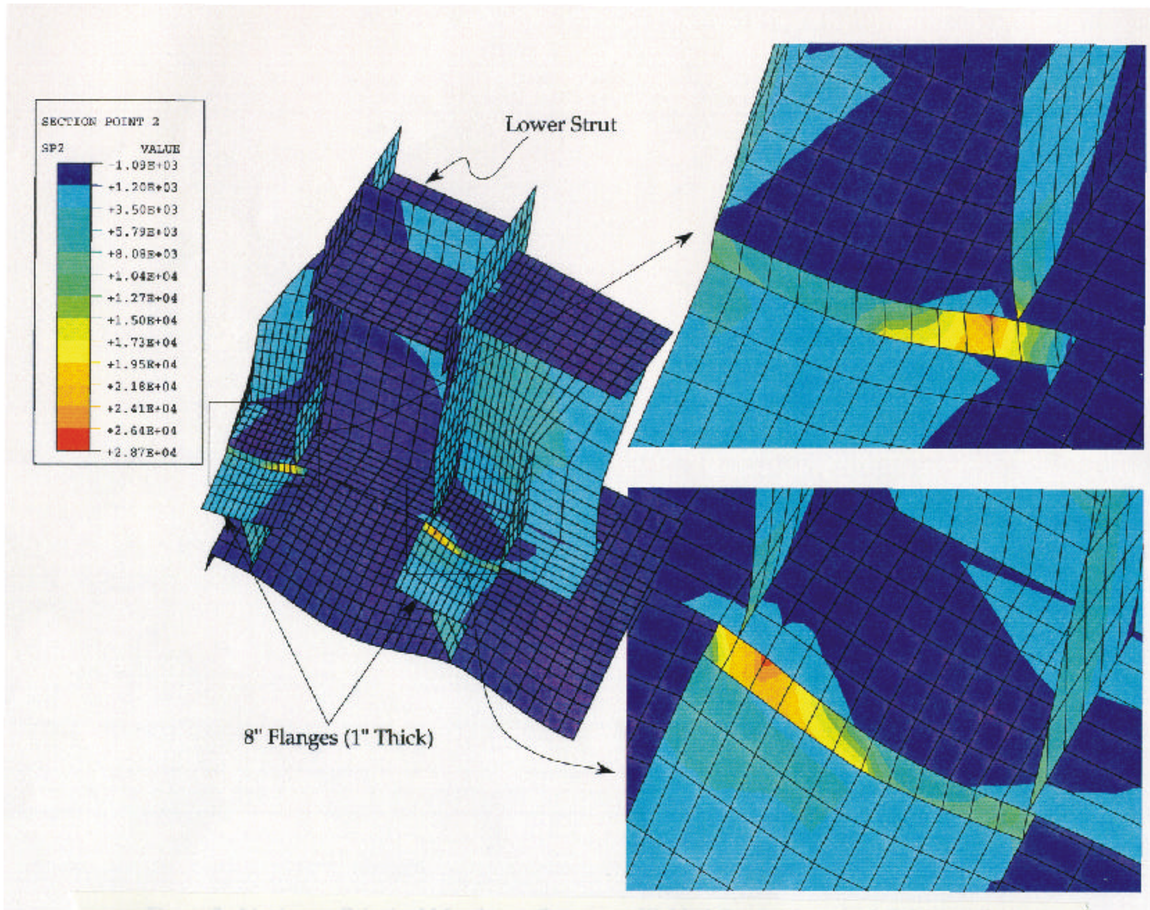


Figure 6.5.3.C. Maximum Principal Membrane Stress at Welded Connections for J. T. Myers Culvert Valves

6.5.4 Reliability Model Parameters

The time-dependent reliability analysis for the vertically-framed reverse tainter culvert valves was developed to estimate the hazard rate for these structures. Similar to the miter gate and horizontally-framed valve reliability models, the reliability analysis for vertically-framed valves incorporates both the fatigue and corrosion of the welds at the girder/rib connections of the valves. Additionally, the engineering team performed a range of 3-D finite element analyses of the valves to investigate the potential modes of failure of the valve, redistribution of loads upon failure, and the realistic values of stresses (both residual, static, and dynamic) to utilize into the reliability model. The limit state incorporated into the reliability model is based on the initiation of a crack at the girder/rib weld interface that causes a failure of the welds at the rib, which causes a redistribution of loads to the welds at the adjacent ribs. As evidenced from the valves at Smithland (same type as J.T. Myers), actual field experience was used in the modeling effort to calibrate the timing of the limit state for the valves. For this model, the engineering team decided to develop a Visual Basic coded model specifically for the ORMSSS vertically-framed reverse tainter culvert valves which was modeled similar to one developed for the miter gates and horizontally-framed culvert valves. The Visual Basic model was named VFCVWELD for the reliability of vertically-framed reverse tainter culvert valves.

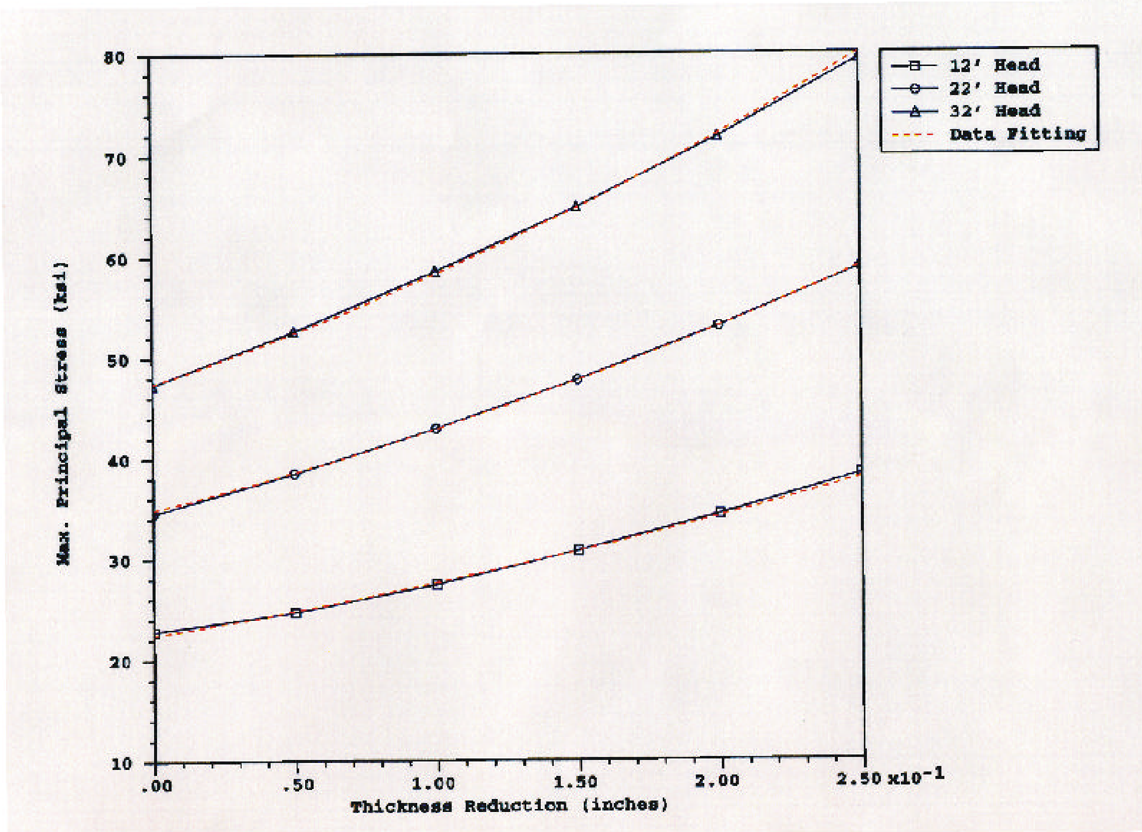


Figure 6.5.3.D. Principal Stress at Welded Connection as Function of Head and Thickness Reduction Due to Corrosion

VFCVWELD Reliability Model

The computer program VFCVWELD has been developed to complete a reliability analysis of the vertically-framed culvert valves for ORMSS lock projects. The model was developed to measure the future performance of the valves over time relative to the selected limit state. Additionally, the model is used to determine if it is a better decision to replace the valves at some scheduled date as opposed to fixing them after they perform unsatisfactorily.

The basis of the model is to determine the time dependent reliability for the valve structure subjected to fatigue and corrosion. Therefore, input items such as paint history, corrosion rates, historical operating head with cycle information, and other random variables are used in the model to determine the time dependent reliability of the structure. Using the analysis and limit state information defined from the finite element modeling, VFCVWELD computes the time dependent reliability of the vertically-framed culvert valves given the input parameters. For each iteration, the model determines the year in which a fatigue-related crack initiates and marks that year as the time of unsatisfactory performance. This is done for each iteration and the results are tabulated for the hazard function in a separate file.

Lock Information. The first portion of input is the project name and chamber that is being analyzed. For each of the ORMSS locks, both the main chamber and auxiliary chamber valves are of the same design and construction technique. However, operating cycles and age are different for the chambers and thus, each must be analyzed separately. The input menu from VFCVWELD for the lock information is to specify the district, lock project, and chamber that is being analyzed.

Rib/Girder Properties. The VFCVWELD program requires the input of rib and girder properties for the valve. Since the original model was calibrated to the performance at Smithland, most of the figures will reference Smithland vertically-framed valve properties. The input menu for the valve properties includes the vertical spacing between ribs, the length of the valve, the top dimension distance to the horizontal girder which defines the positions of both the top and bottom girders on the vertical ribs (for simplicity, the top and bottom ribs were assumed to be equidistant from both ends since all differences are very minor), the rib flange width, the horizontal girder flange width, and finally both the horizontal and vertical weld thickness at the rib/flange connection. The input for these properties in VFCVWELD for the Smithland valves are shown in Figure 6.5.4.A.

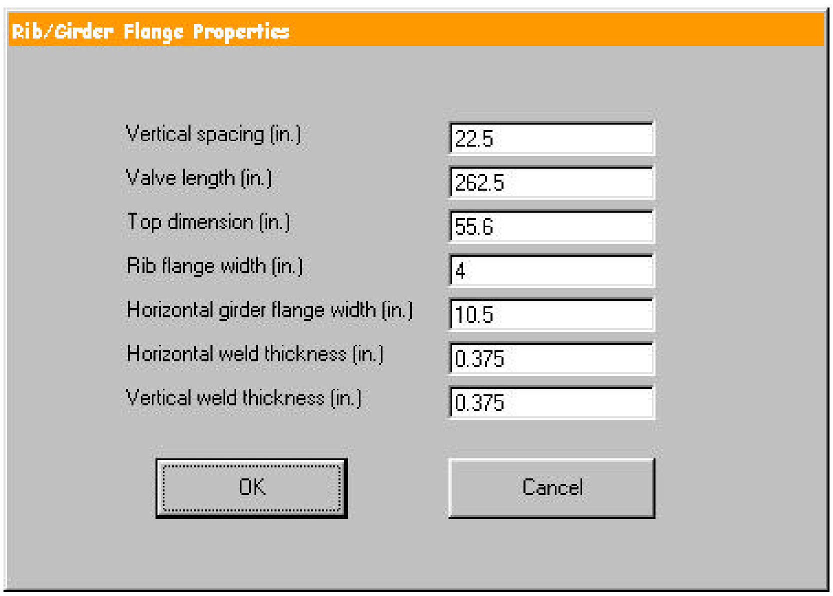


Figure 6.5.4.A. Rib/Girder Flange Properties Input Menu

Crack Parameters. The only crack parameter required for the VFCVWELD is the initital crack length. This is because the reliaibility model only accounts for the crack initiation and not crack propogation because of the anticipated brittle failure mode that was evidenced at Smithland. The initial crack length is set to a default value of 0.25 inches, the same as the miter gate initial crack length.

Head Histogram. The head histogram reflects the actual past distribution of head differential and hydraulic cycles for the reverse tainter valves. This distribution is based on true daily lockage cycles available from the Lock Performance Monitoring System (LPMS) combined with the true head differential for each day. This distribution is very valuable in determining the fraction of annual cycles versus the expected head differential that can be used for fatigue analysis. The head histograms developed by WES are based on data collected and analyzed for approximately 12 years (1984–1996) of lock operation. The VFCVWELD program allows the input of up to 20 different blocks for head (at specified midpoints) and fraction of cycles from the histograms. This histogram is used in VFCVWELD to parse the input annual cycles into the defined stress range blocks and number cycles for fatigue analysis. An example head histogram is shown in Figure 6.5.4.B for Markland Lock and Dam (even though Markland valves are horizontally-framed the histograms are similar in nature).

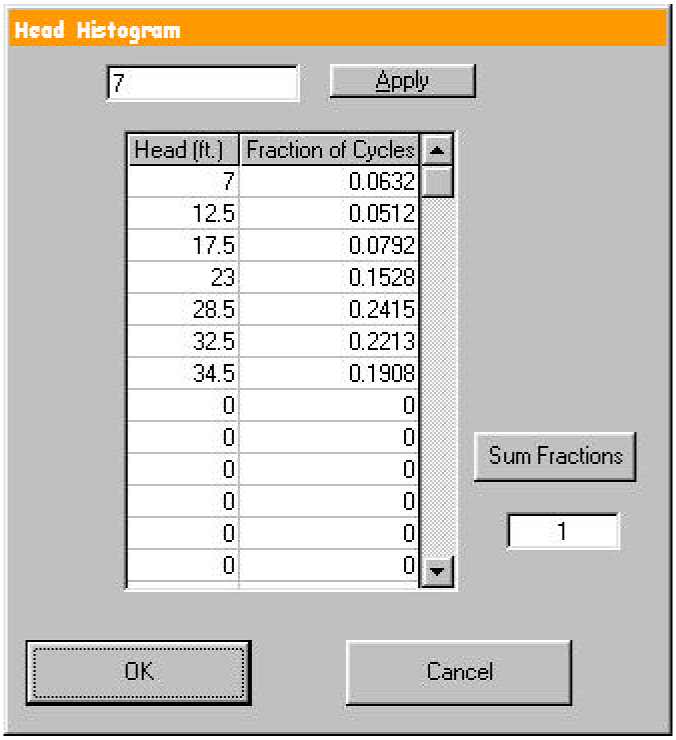


Figure 6.5.4.B. Example of Head Histogram

Traffic Cycles. The number of operating cycles for the vertically-framed valves are determined for each lock based on actual and predicted future cycles for the study period. The cycle information is used in fatigue analysis incorporated into the VFCVWELD program. The cycles are input from the start of operation to the end of the study period. Operating cycles from the origination of the project through 1984 were determined by going through the log books at various ORMSS sites to determine the number of lockages in each chamber. From the LPMS data from 1984 through 1996, a ratio of lockages to operating cycles was determined and assumed to be the same in the past as well as for future projected cycles. Traffic cycles for 1985 through 1996 was determined using LPMS data. Finally, projected traffic through the end of the study period was determined by LRD's Navigation Center in Huntington, WV. The input traffic cycles for one of the Smithland 1200-ft chambers is shown in Figure 6.5.4.C.

Random Variables Used in VFCVWELD

The random variables incorporated into the VFCVWELD analysis are the yield strength of A36 steel, corrosion rate, residual stress factor, stress concentration factor, and the dynamic amplification factor. The values and ranges for the yield strength used for the vertically-framed valve analysis are the same as applied to the miter gates and horizontally-framed culvert valves. The corrosion rate selected was for a structure subjected to wet/dry applications because the valves are constantly in and out of the water during operation, again the same as the horizontally-framed culvert valves. This rate is termed in the "splash" zone

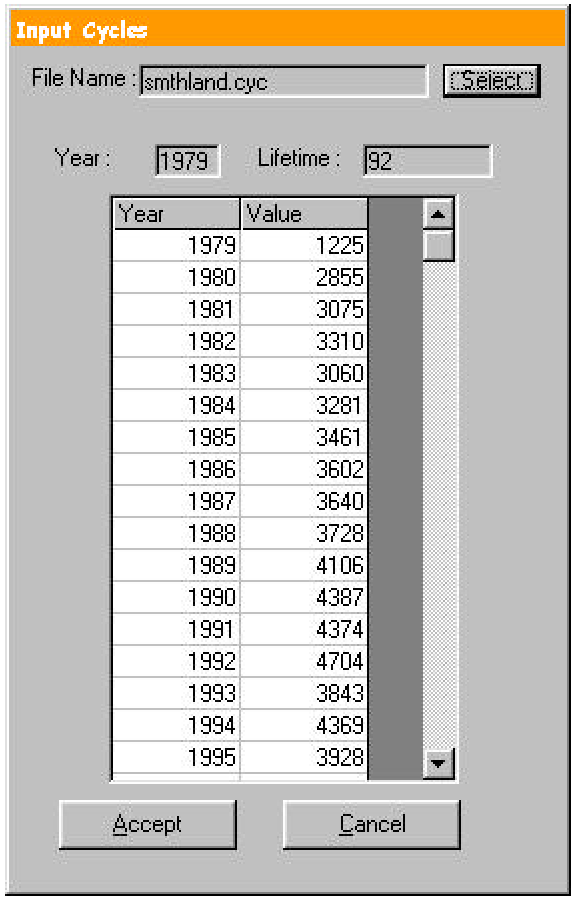


Figure 6.5.4.C. Example Input Traffic Cycles

and has a higher corrosion rate than a submerged structure. Additionally, it was assumed that the valves only had an initial effective paint life of 5 years because of the turbulent water conditions impacting the valve during filling and emptying operations. This was based upon engineering judgment. However, sensitivity analyses were conducted varying the "effective" paint life from 0 to 20 years and it did not turn out to be a controlling variable. Therefore, the five-year life was used to be consistent with the analysis for the horizontally-framed culvert valves. Because a detailed residual stress analysis was not possible for this model due to funding and schedule constraints, a residual stress factor and stress concentration factor was created to attempt to measure the randomness associated with the residual stress analysis required for this model. The factor was based upon the residual stress analysis completed for the Markland miter gates. This is also consistent with the analysis for the horizontally-framed culvert valves. Finally, a dynamic amplification factor was needed to measure the increase in load on the valve due to the high velocities that occur during filling and emptying operations. This value (along with appropriate range) was determined by using a steady state fluid-structure interaction finite element model. This model is described in the horizontally-framed valve narrative. Again, all random variables were selected using Monte Carlo simulation techniques.

Yield Strength. The distribution for yield strength is based on data from the published literature and previous Corps of Engineers reliability studies. The distribution is based on a truncated lognormal with a nominal yield stress of 38.88 ksi (i.e., mean yield strength times the strength ratio) and a standard deviation of 5.44. The lower limit for truncation is based on one standard deviation below the nominal (33.44 ksi) and the upper limit is based on approximately two standard deviations above the nominal (51 ksi). The distribution and statistical moments for yield strength of the steel are the same as used for the miter gates and horizontally-framed culvert valves.

Corrosion Rate. The distribution for corrosion is based on the data from the published literature and previous Corps of Engineers reliability studies. Corrosion is based on a power law that has been fit to actual field data in various corrosive environments. The equation used for the corrosion is $C(t) = A*t^B$, where A is a random variable based on field measurements, B is generally a constant based on different corrosive environments and C(t) is the corrosion in micromils/yr. For this report, the mean value of A was selected based on "splash zone" corrosion. This distribution used for A was a truncated lognormal with a mean value was 140 and standard deviation of 42. The upper limit of the distribution was taken at 224 and the lower limit at 56. The value for B was a constant of 0.667. These limits and constants are based on actual field measurement of hydraulic steel structures.

Residual Stress, Stress Concentration, and Dynamic Amplification Factors. Three types of factors are utilized in VFCVWELD to account the major differences in stress values between traditional hand calculations and the more sophisticated finite element analysis. The residual stress factor represents the tensile stresses that are created during the heating and subsequent cooling of the welds at the time of construction. The second factor is the dynamic amplification factor, which represents increased load on the valve that is created by the vortex flow and pressure differential of the water around the valve upon opening. This quick change in pressure increases the stresses on the strut arms during valve operation. The third factor is the stress concentration factor that tries to account for local stress increases to due fabrication confinements that occur in welded structures. An extensive literature search for field measurement data on these factors was conducted. No data is available to assist in better defining any these parameters for the reliability of the valve. Therefore, these adjustments were determined based on various finite element analysis to determine the range of values that may be exhibited in these random variables.

The distribution for the residual stress model factors was considered to be a gaussian distribution since the limits were defined by a concentration about a certain percent ratio. The mean value for the residual stress was 0.35 with a standard deviation of 0.05. The dynamic amplification factor was also determined to be a normal distribution with a mean of 1.25 (25% increase) and a standard deviation of 0.025 (2.5%). The stress concentration factor for the J.T. Myers valves (Group 2) was determined to be an uniform distribution with an upper limit of 2.1 and a lower limit of 1.5.

6.5.5 VFCVWELD Reliability Model Results and Event Trees

The output from the VFCVWELD reliability model is a hazard function giving the annual probability of unsatisfactory performance of the culvert valve over time. For simplicity, it was decided to look only at the reliability associated with a single valve as compared to numerous ones for the main chamber. This was done because of the type of failure that is being investigated in the model would cause such concern regarding the condition of the other valves, that the chamber would be shut down at least temporarily for inspection and repair to the remaining three valves. Additionally, the engineering team working on the valves thought the differences between the main chamber and auxiliary chamber could essentially be worked out in the event trees regarding lock chamber closure and repair scenarios.

Main Chamber Results and Event Tree

The hazard rate associated with a single culvert valve in the main chamber is significant for J. T. Myers as the valve reaches the end of its original design life (assumed to be 50 years). The main chamber culvert valve probability of unsatisfactory performance initially becomes a non-zero value in the year 1993. The hazard rate reaches 1% in year 2004, and reaches a value of 5% in 2021, and peaks at 21% in 2070. The annual hazard rates are shown graphically in Figure 6.5.5.A.

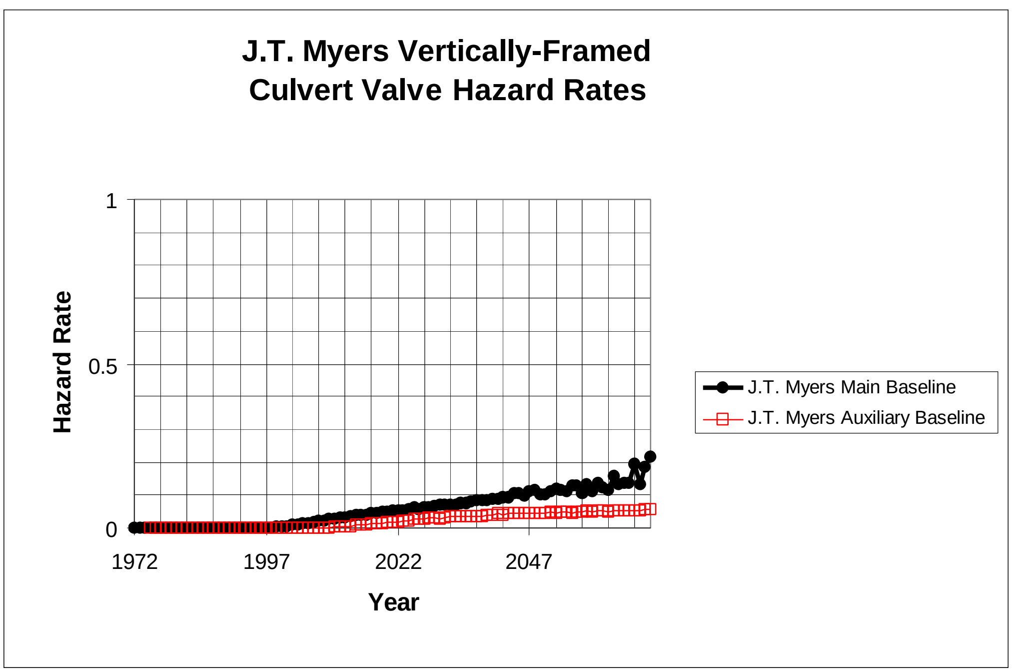


Figure 6.5.5.A. J.T. Myers Culvert Valve Hazard Rates

The event tree for the main chamber culvert valves is different than the one for the auxiliary chamber. Because the redundancy associated with the valves on the main chamber, it is possible to operate the main chamber on only two valves as opposed to four, although the filling and emptying time is roughly doubled over normal operation. However, the doubling of filling and emptying time does not begin to compare to the navigation disbenefits associated with having the main chamber closed and needing to move large tows through the smaller auxiliary chamber. Therefore, it was decided that separate event trees were needed for the two chambers. The event tree for the main chamber is shown in Figure 6.5.5.B. A similar format as used for the miter gate event tree was used for the valves. Assuming an unsatisfactory performance of the culvert valve based upon the limit state, three possible repair scenarios were chosen. A breakdown of these repair scenarios, along with their costs and closures are provided for the event tree.

Catastrophic Failure, Install 4 New Valves. This repair assumes the worst situation, a catastrophic failure of a culvert valve. It is assumed the damage and potential problems associated with it are enough to warrant a significant closure of the main chamber. Because the main chamber could be put back in service with only two valves, the repair scenario assumes that the chamber would not be opened again until temporary repairs can be completed on two of the valves. The closure in the year of the failure is assumed to be 15 days to complete inspections and emergency repairs to the other filling and emptying valves. It is assumed that 30 additional days are required to make extensive, temporary repairs to the failed valve. The following year four new valves would be installed in a manner such that the chamber is never closed, but operates at half-speed filling and emptying times for 90 days. Future reliability is assumed to be equal to 1.0 for the remainder of the study since new valves are installed. The repair cost associated with this repair is $3,650,000. This amount is split over two years. A breakdown of the costs is supplied below.

Year of failure, assumes emergency conditions

Repair fleet on site 45 days at $10,000 per day →	$ 450,000
Emergency fabrication of 4 new valves (4 at $500,000 each) →	$2,000,000
Following year, install 4 new valves	
Repair fleet on site 120 days at $10,000 per day →	$1,200,000
Total for Catastrophic Repair Cost →	$3,650,000

It is assumed that the chance of a catastrophic failure of this magnitude is quite low, therefore, it was decided to only place about a 1% chance of this occurrence on this branch. Additionally, the cost of fabricating the valves is increased by 25% for the assumption all work would occur under emergency conditions.

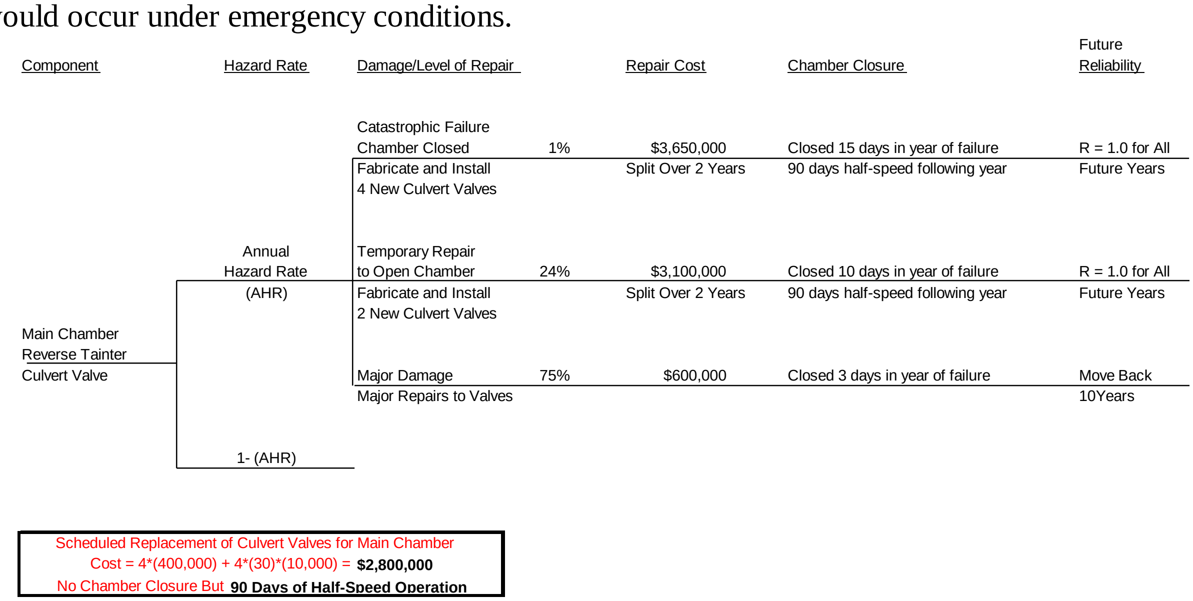


Figure 6.5.5.B. J.T. Myers Main Chamber Reverse Tainter Valve Event Tree

Temporary Repair with New Valves Following Year. This repair assumes that the major damage has occurred to one of the four valves. The chamber is assumed closed for 10 days. This includes time for the repair fleet to organize and get to the site. This could be several days under the best circumstances. The remaining time is for the inspection and repair to at least two of the valves to open the chamber. An additional 20 days is required for the emergency repair to the other two valves. Then four new valves are fabricated and delivered to the site in the following year for installation. Installation is assumed to take 120 days, with about 90 days having the chamber at ½ filling and emptying speed. The repair cost for this alternative is estimated to be $3,100,000 with chamber closure time of 10 days. There is an additional 90 days of the main chamber operating at half speed. Future reliability is assumed to be equal to 1.0 for the remainder of the study since new valves are installed the following year. A breakdown of the costs for this repair is supplied below.

Year of failure, assumes emergency conditions

Repair fleet on site 30 days at $10,000 per day →	$ 300,000

Following year, install 4 new valves

Emergency fabrication of 4 new valves (4 at $400,000 each) →	$1,600,000
Repair fleet on site 120 days at $10,000 per day →	$1,200,000
Total for Temporary Repair with New Valves →	$3,100,000

It was agreed that this scenario represented a reasonable chance of occurring regarding repair technique, thus, 24% was placed on this branch. It is believed that the repair fleet would do everything possible to get the chamber operational again, however, major damage would prompt the district to obtain the funds to procure new valves.

Major Repair, Leave Existing Valves. This repair assumes the least damage to the culvert valves, such that they are repairable and can continue in service. For this situation, the main chamber is assumed to be closed for 3 days for inspection and repair to the culvert valves. However, it is assumed the repair fleet will be on-site for a total of 60 days for extensive repairs to all four valves to extend their serviceable lives. The cost associated with this alternative is $600,000. Almost all of the repair time would be with the main chamber operating at half-speed. Since the existing valves are left in place, it is assumed the repair would only improve the reliability of the structure by an “effective” ten years. Therefore, the updated reliability in the following year resets to the value it was 10 years before the failure. Again, this was the easiest way to reset hazard rates for the economic analysis. A breakdown of costs associated with this repair is provided below.

Year of failure

Repair fleet on-site for 60 days at $10,000 per day →	$600,000

The $600,000 cost reflects the total for this scenario. Along with operations review, it was decided that this repair scenario represents the most likely solution. Therefore, the remaining 75% was applied to this branch.

Scheduled Replacement of Culvert Valves. The other piece of information the economists need is the cost and chamber closure or filling/emptying effect associated with the scheduled replacement of the valves before failure. There are four valves for the main chamber and it can be operated at half-speed in the event of repair or replacement work to one of the valves. The cost and closure breakdown associated with a scheduled replacement of the main chamber culvert valves is provided below.

Year of scheduled replacement

Fabrication and delivery of 4 valves ($400,000 each) →	$1,600,000
Repair fleet time (4 valves x 30 days each x $10,000 per day) →	<u>$1,200,000</u>
Total cost to replace all 4 valves of main chamber →	$2,800,000

Auxiliary Chamber Results and Event Tree

The annual hazard rates for a single culvert valve in the auxiliary chamber for J. T. Myers is also shown in Figure 6.5.5.A. As expected, the hazard rate is lower than for the main chamber culvert valves. This is due to the fact that both are of the same design, but the auxiliary chamber has seen less historic cycles. The auxiliary chamber culvert valve probability of unsatisfactory performance initially becomes a non-zero value in the year 2001. The hazard rate reaches 1% in year 2017, a value of 5% in 2057, and peaks at 5.5% in 2070.

The event tree for the auxiliary chamber culvert valves is different than one for the main chamber because there are only two valves for the auxiliary chamber. Therefore, any problems associated with either of the auxiliary chamber valves causes a complete closure of that chamber, whereas, it is possible to operate the main chamber at ½ speed during valve repairs. The event tree for the auxiliary chamber is shown in Figure 6.5.5.C. The format and percentages were kept the same as the main chamber valves. The only differences lie in the cost and closure times associated with each repair when compared to the event tree for the main chamber culvert valves.

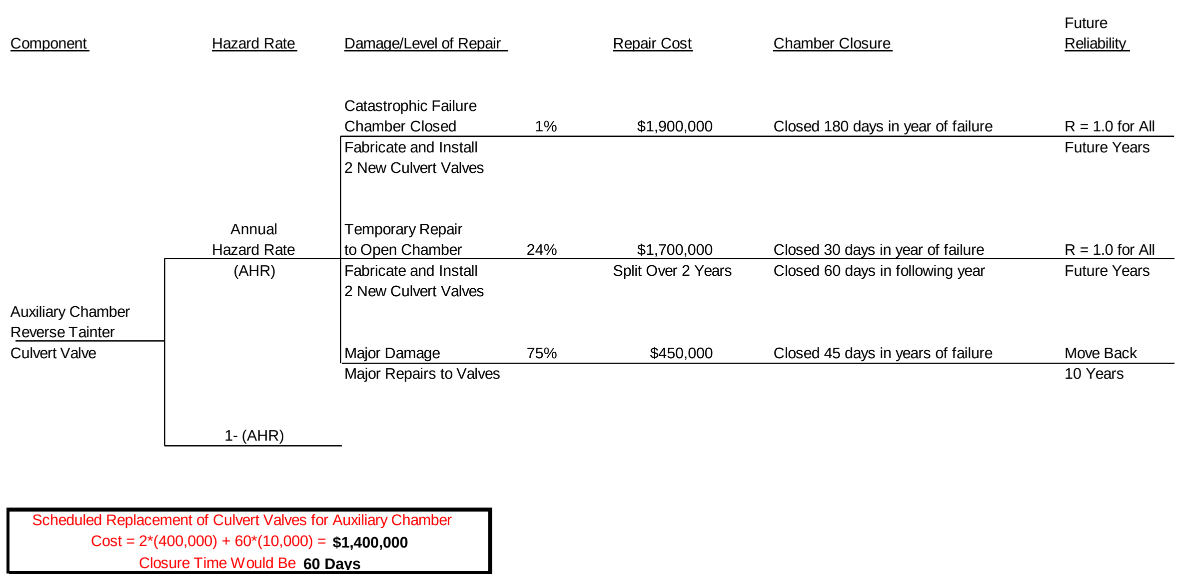


Figure 6.5.5.C. J.T. Myers Auxiliary Chamber Culvert Valve Event Tree

<u>Catastrophic Failure, Install 2 New Valves.</u> This repair assumes the worst situation, a catastrophic failure of a culvert valve. It is assumed the damage and potential problems associated with it are enough to warrant an extended closure of the auxiliary chamber for the replacement of both culvert valves. It is assumed emergency fabrication of two new valves

would occur immediately as there are not spare valves for the J.T. Myers project. Future reliability is assumed to be equal to 1.0 for the remainder of the study since new valves are installed. The repair cost associated with this repair is $1,900,000. This amount is assumed to occur in the year of the failure. A breakdown of the costs is supplied below.

Year of failure, assumes emergency conditions

Repair fleet on site 90 days at $10,000 per day →	$ 900,000
Emergency fabrication of 2 new valves (2 at $500,000 each) →	$1,000,000
Total for Catastrophic Repair Cost →	$1,900,000

It is assumed that the chance of a catastrophic failure of this magnitude is quite low, therefore, it was decided to only place a 1% chance of this occurrence on this branch. Additionally, the cost of fabricating the valves is increased by 25% for the assumption all work would occur under emergency conditions.

Temporary Repair with New Valves Following Year. This repair assumes that the major damage has occurred to one of the valves. The chamber is assumed closed for 30 days. This includes time for the repair fleet to organize and get to the site. This could be several days under the best circumstances. The remaining time is for the inspection and repair to both valves. Then two new valves are fabricated and delivered to the site in the following year for installation. Installation is assumed to take 60 days, for which the auxiliary chamber will be closed. The repair cost for this alternative is estimated to be $1,700,000 with chamber closure time of 30 days in the year of failure, followed by 60 days of closure for new valve installation the next year. Future reliability is assumed to be equal to 1.0 for the remainder of the study since new valves are installed the following year. A breakdown of the costs for this repair is supplied below.

Year of failure, assumes emergency conditions

Repair fleet on site 30 days at $10,000 per day →	$ 300,000

Following year, install 4 new valves

Emergency fabrication of 2 new valves (2 at $400,000 each) →	$ 800,000
Repair fleet on site 60 days at $10,000 per day →	$ 600,000
Total for Temporary Repair with New Valves →	$1,700,000

It was agreed that this scenario represented a reasonable chance of occurring regarding repair technique, thus, 24% was placed on this branch. It is believed that the repair fleet would do everything possible to get the chamber operational again, however, major damage would prompt the district to obtain the funds to procure new valves.

Major Repair, Leave Existing Valves. This repair assumes the least damage to the culvert valves, such that they are repairable and can continue in service. For this situation, the auxiliary chamber is assumed closed for 45 days for repair to both culvert valves. The cost associated with this alternative is $450,000. Since the existing valves are left in place, it is assumed the repair would only improve the reliability of the structure by an “effective” ten years. Therefore, the updated reliability in the following year resets to the value it was 10 years before the failure. Again, this was the easiest way to reset hazard rates for the economic analysis. A breakdown of costs associated with this repair is provided below.

Year of failure

Repair fleet on-site for 45 days at $10,000 per day → $450,000

The $450,000 cost reflects the total for this scenario. Along with operations review, it was decided that this repair scenario represents the most likely solution. Therefore, the remaining 75% was applied to this branch.

Scheduled Replacement of Culvert Valves. The other piece of information the economists need is the cost and chamber closure or filling/emptying effect associated with the scheduled replacement of the valves before failure. There are two valves for the auxiliary chamber and replacement requires closure of the chamber. The cost and closure breakdown associated with a scheduled replacement of the main chamber culvert valves is provided below.

Year of scheduled replacement

Fabrication and delivery of 2 valves ($400,000 each) →	$ 800,000
Repair fleet time (2 valves x 30 days each x $10,000 per day) →	$ 600,000
Total cost to replace all 4 valves of main chamber →	$1,400,000

6.5.6 Economic Results for Vertically-Framed Culvert Valves

Using the culvert valve hazard rates for each chamber and the chamber specific event trees, it can be determined if it is economically justified to replace the culvert valves prior to failure. The economists use the data provided by the engineering team to determine average annual costs associated for the fix-as-fails approach, in addition to determining average annual costs for replacing the valves in different years. The option with the lowest average annual cost sets the timed replacement of the valves. Table 6.5.6.A summarizes the average annual costs associated with the culvert valves for J.T. Myers. As evidenced by the values in the table, the main chamber culvert valves at J.T. Myers are not justified for replacement until around 2010, once that option becomes lower than the fix-as-fails option. However, the optimum time to replace the main chamber culvert valves is 2030 as evidenced by the lowest average annual cost. The auxiliary chamber culvert valves are justified for immediate replacement, but are also optimally timed around 2030. Again, all other sites with vertically-framed culvert valves will have a similar engineering and economic analysis conducted for them. Their results will be available for the ORMSS final report.

Table 6.5.6.A. Economic Results for J.T. Myers Culvert Valves

Economic Analysis of J.T. Myers Culvert Valves		
Description of Option	Chamber	Average Annual Cost
Fix-as-Fails	Main	$274,700
Replace in 2000	Main	$433,100
Replace in 2010	Main	$249,300
Replace in 2020	Main	$190,700
Replace in 2030	**Main**	**$172,900**
Replace in 2040	Main	$195,400
Fix-as-Fails	Auxiliary	$435,500
Replace in 2000	Auxiliary	$333,600
Replace in 2010	Auxiliary	$197,000
Replace in 2020	Auxiliary	$130,700
Replace in 2030	**Auxiliary**	**$92,300**
Replace in 2040	Auxiliary	$175,000

6.6 ELECTRICAL SYSTEM RELIABILITY FOR THE LOCK

The electrical system for the lock essentially is made up of a series of individual components that work in series and parallel to operate the lock. Included in this list of components are items like commercial power source, diesel generator, fuses, motors, controllers, solenoids, etc. The electrical model was kept a single model in that the team decided not to try to develop separate hazard rates for each specific component. Since the vast majority of the system operates in series, a failure of any single item, with the exception of the possibly the diesel generator, would shut the lock down until repairs were made. Therefore, a single overall lock model was set up for the development of one hazard rate per chamber with a single event tree.

Due to schedule and funding constraints, only the electrical system results for J.T. Myers and Greenup were totally completed (runs calibrated, through ITR, etc.) at the time of this interim report. Therefore, this section will only detail the results for these two sites. The reliability assessments of all other Ohio River projects will be completed as part of the overall ORMSS final report. The reliability results for the electrical systems at J.T. Myers and Greenup will be carried forward into the final ORMSS report.

6.6.1 Assessment of Reliability for Electrical System of the Lock

The electrical reliability assessment is based on procedures defined by ETL 1110-2-549, Engineering and Design, RELIABILITY ANALYSIS OF NAVIGATIONAL LOCK AND DAM MECHANICAL AND ELECTRICAL EQUIPMENT, 30 Nov 1997. The following paragraphs document the assumptions, current conditions and provide the results of the reliability assessment.

6.6.2 Component Condition Investigations

Both J.T. Myers and Greenup have two locks, a main, 1200-ft. lock, and an auxiliary, 600-ft. lock. J.T. Myers became operational in 1972. Greenup became operational in 1959. Each lock has four miter gates that are operated by hydraulically driven sector gears. The electrical power is provided by the local utility, with backup power provided by a diesel generator. Most of the electrical equipment, excepting that replaced during regular maintenance, is the original equipment at both projects.

6.6.3 Condition States of the Electrical System

The reliability, R(t), for each component and for the system as a whole, was calculated for every year of operation from installation through the year 2070. The limit state was defined as the Mean Time to Failure (MTF) for the expected useful life of the components being analyzed. The hazard rate of any system is defined by the following relationship to be the probability of unsatisfactory performance, provided the component or system has not failed until the time of assessment: $h(t)=f(t)/R(t)$.

The general reliability block diagram and one-line of the basic electrical system for both J.T. Myers and Greenup are shown in the at the back of Section 6.6 in Figure 6.6.3.A. The title within the figure depicts the electrical scheme at Markland. The one-line diagrams for Markland are similar to both J.T. Myers and Greenup and the figure is provided to show an overall electrical system for a typical ORMSS project. Note that the Markland diagram was readily available from a previous report and therefore, is provided as an example since both J.T. Myers and Greenup are very similar.

6.6.4 Failure Rate of Electrical Components

The environmental conditions were considered for the ambient service of the electrical equipment. Lambda, λ, represents the number of failures per 1×10^6 operating hours. The values were based on data from equipment in similar service conditions. The failure rates of all applicable equipment were based on published data and engineering judgement based on repair history and length of time parts are generally readily available for a given serviceable component.

6.6.5 Failure Types

In this analysis, electrical equipment comes to the end of its "useful life" by one of three types of failures. These are termed the *Duty Cycle Failure, Environmental Conditions/Entropy*, and *Obsolescence*. Each is described within this sub-section.

Duty Cycle Failure

This type of failure is based on the amount of time that the component is operated or how many cycles it has to go through multiplied by the time per cycle. Since the equipment does not operate continually, the total mission time is determined with a duty cycle factor. The duty cycle factor is the ratio of actual time the equipment is energized by voltage and/or current to the total mission time, t. The example from ETL 1110-2-549 states that the equation $R(t) = e^{-\lambda td}$ is a constant failure rate component with a duty factor d. The lock equipment in the example had an average number of 13,148 open/close cycles per year. Assuming the operating time of an open/close operation is 120 seconds (or 240 seconds per open/close cycle) and using a total mission time of 50 years, then,

$$\begin{aligned}\text{Operating time} &= (240*13{,}148)/3600 \\ &= (877\text{ operational hours/year})*(50\text{ years}) \\ &= 43{,}850\text{ hours} = 5\text{ years}\end{aligned}$$

For t = 50 years,

$$d = 5/50 = 0.10$$

This analysis uses the past and projected cycles as a key input to this analysis. To determine the duty cycles for each component, see Figure 6.6.5A in the back of this narrative, which shows some of the model computations for the main chamber electrical system for J.T. Myers. The first page of the model for J.T. Myers main chamber is provided in this report only since all the computation sheets are similar for all projects, including Greenup. The total number of cycles for each lock is divided by the total number of years of operation to come up with the average cycles per year. Electrical equipment, which is normally energized 100% of the calendar year, has a duty cycle of 1.0.

Environmental Conditions and Entropy

This type of failure relates to components such as a wire, which has insulation that degrades over time, whether it has current flow or not. In this case, historic replacement information is used. For example, several locks have installed new wiring after approximately 50 years of operation. While this replacement was more of a preventative measure than a repaired failure, it does define the "useful life" that was utilized from the component and provides a guide for subsequent replacements. In this analysis, useful life is equal to characteristic life, α.

Obsolescence

Components such as the motor control center (MCC) and transfer switches usually reach the end of their “useful life” when repair parts and other relative hardware cease to be available from the manufacturer. These components will usually require repair/service before they become obsolete, but this analysis does not consider them failed until parts are not readily available. Historic precedent and engineering judgement must be used for the values of these components.

6.6.6 Model Distribution

The modes of failure for electrical equipment are very complex (i.e. they involve a wide variety of distresses such as temperature, vibration, mechanical stresses, etc.) resulting in extreme difficulty or inability to select β values for a Weibull distribution. Since the values were not known, an initial value of 1.0 was used as recommended by ETL 1110-2-549. Using an initial value of 1.0 tends to reduce the Weibull distribution equation to an exponential distribution for the computation of the reliability value. After initial results indicated exceedingly high hazard rates, it was decided to try other β values for “key components”. After several variations, it was agreed by the engineering team to use a value of 2.5 for the motor control center, panel board, controller, and motors. This combination of β values seemed to give the proper range of values for the overall hazard rate. The exponential reliability equation is:

$$R(t) = e^{-\lambda' t'}$$

where,

λ' = adjusted failure rate, failures/year
t'= adjusted time variable (operation time), years

One other key item to note is that several “small” components such as fuses, solenoids, switches, and circuit breakers were set to be 100% reliable for the entire study period. Because these components could be repaired without closing the chamber, and at a very minor cost, the team decided to “eliminate” these from the failure calculations and assume they were always working properly. Making these “minor failures” part of the overall calculation tended to yield a very high hazard rate that did not seem realistic when determining the long-term reliability of the electrical system. Another reason that these values were selected was the overall reliability process agreed by the team. The team believed the better option for all of the reliability models (miter gates, culvert valves, etc.) was to investigate significant type of limit states, thus, ones that caused extended chamber closures and had high repair costs. All the components that were made 100% reliable for this study would cause neither an extended chamber closure nor costly repair if they failed to perform satisfactorily.

6.6.7 Lock Electrical Sub-Components Analyzed

The overall system analyzed was the provision of power to operate the lock. The overall system was modeled as described by ETL 1110-2-549. The entire system for J.T. Myers is shown in Figure 6.6.3.A in the back of Section 6.6. Because all the systems are generally the same for Louisville District locks, the reliability block diagram for Markland is shown to be representative for J.T. Myers because the Markland diagram was readily available from a previous report. Greenup's electrical distribution is very similar to J.T. Myers with minor differences described for each sub-component below. There is no recorded historical data available regarding the lock electrical components or system reliability. Much of the reliability information for the electrical components was readily available in published sources, which was also referenced by ETL 1110-2-549. However, some of the published reliability information was not based on operating conditions or environment similar to the site and required calibration. Therefore, the team used varying β values and made minor components 100% reliable to develop "common sense" results.

Lock Electrical Service to the Project

The lock electrical service for J.T. Myers is comprised of two power sources, the electric utility service entrance, (CP, commercial power), and the standby diesel generator, (DG) with wire (WP, wire, power), fuses, (F), and circuit breakers (CB) which feed the motor control center (MC). The power sources are "stand-by redundant" because the system continues to operate successfully if either of the sources operate and as long as power is transferred successfully. The J.T. Myers electrical distribution subsystem diagram for power to the project is organized as shown in Figure 6.6.7.A. The distribution subsystem for Greenup is similar but not exactly the same as J.T. Myers and is shown in Figure 6.6.7.B. The reliability calculations in the spread sheet reliability model, see Figure 6.6.5.A for an example of the J.T. Myers computation sheets within the overall lock electrical reliability model, reflect these differences between the sites.

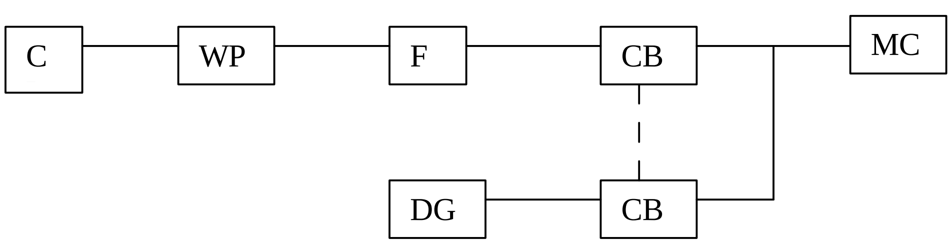


Figure 6.6.7.A. J.T. Myers Lock Electrical Service Block Diagram

The resulting reliability equation for this segment of the J.T. Myers electrical distribution system is:

$$R(t)_{JTMyers} = [1-[[1-CP(t)*WP(t)*F(t)*CB(t)]*[1-DG(t)*CB(t)]]][MC(t)]$$

The block diagram for the delivery of power to the Greenup project is shown below in Figure 6.6.7.B. Note there are slight differences between the Greenup and J.T. Myers sites.

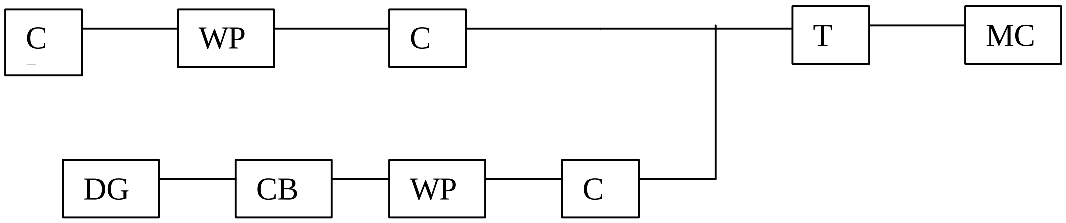


Figure 6.6.7.B. Greenup Lock Electrical Service Block Diagram

The resulting reliability equation for this segment of the Greenup electrical distribution system is:

$R(t)_{Greenup}$ = [1-[[1-CP(t)*WP(t)*CB(t)]*[1-DG(t)*CB(t)*WP(t)*CB(t)]]][MC(t)]

Lock Electrical Distribution, Power to Hydraulic Pumps

Three hydraulic pumps in parallel provide hydraulic power for the gates. Each of these circuits is comprised of a controller/contactor (C), a circuit breaker (CB), and the motor (M) and can operate independently of the other two. The diagram of the resulting electrical subsystem is organized as follows in Figure 6.6.7.C. Both systems are exactly the same for J.T. Myers and Greenup.

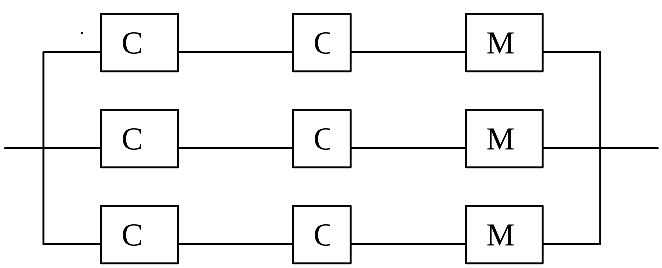


Figure 6.6.7.C Block Diagram for Power to the Three Parallel Hydraulic Pumps

Each of the pump motors (M) is fed from a circuit breaker (CB) through a controller/contactor (C). The resulting reliability equation for this segment of the electrical distribution system is:

$R(t)_{Figure3}$=[1-[1-[CB(t)*C(t)*M(t)]]^3]]

Lock Electrical Distribution, Control Power

Power for the J.T. Myers controls are stepped down with a control transformer (T), that is fed from a circuit breaker (CB). The control power feeds through the control wiring (WC), two circuit breakers (CB), and a panelboard (PB). This control power feeds the open/closed controller (C) which directs the power through the limit switches (LS) to the respective emptying\filling valve (SV).

The diagram of the resulting electrical subsystem at J.T. Myers is organized as follows in Figure 6.6.7.D. The power for the electrical subsystem at Greenup is similar to J.T. Myers, but not exactly the same. The diagram for Greenup is shown in Figure 6.6.7.E.

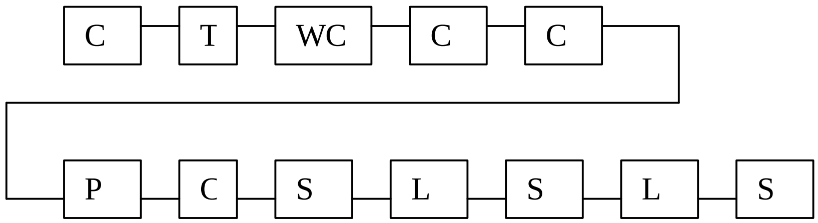


Figure 6.6.7.D. J.T. Myers Block Diagram for Power to the Controls

The resulting reliability equation for this segment of the J.T. Myers electrical distribution system is:

$$R(t)_{JTMyers}=[CB(t)^3*T(t)*WC(t)*PB(t)*C(t)*SV(t)^3*LS(t)^2]$$

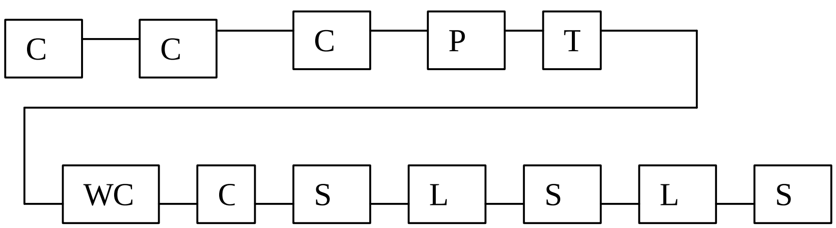


Figure 6.6.7.E. Greenup Block Diagram for Power to the Controls

The resulting reliability equation for this segment of the Greenup electrical distribution system is:

$$R(t)_{Greenup}=[CB(t)^3*PB(t)*T(t)*WC(t)*C(t)*SV(t)^3*LS(t)^2]$$

6.6.8 Electrical System Event Tree

The event tree for the electrical system is set up slightly different than that of the structural components. An extra branch on the event tree was added to differentiate between minor and major types of failures of the significant electrical components. The failure rates from the manuals reflect mainly wear-and-tear type of failures such that most repairs would be minor in nature. Therefore, the first branch of the event tree is the hazard rate for the electrical system. The second branch delineates between major and minor failures. The engineering team used 25% for major and 75% for minor given the components within the electrical system. The event tree is shown in Figure 6.6.8.A. A cost and closure breakdown for each of the major and minor types of repairs is supplied for the event tree.

Major Failure Branch

There are three branches off of the major failure branch portion of the event tree. These are catastrophic failure with a new, unplanned electrical system, a major overhaul of the electrical system, and finally, replacing one major component. Each of these is detailed below.

Major Failure, Unplanned New Electrical System. This assumes a total failure of the electrical system. The failure is assumed to be non-repairable such that a new, unplanned electrical system is required for the lock. It is assumed that the electrical system would cost $4,575,000 to replace under emergency conditions. The specialty rate was assumed to cost half of the regular fleet rate for a full dewatering. Full fleet rate for a dewatering is approximately $35,000 per day from recent dewaterings for the Louisville District. More importantly, the chamber is assumed closed for 90 days while replacement of the electrical system is completed.

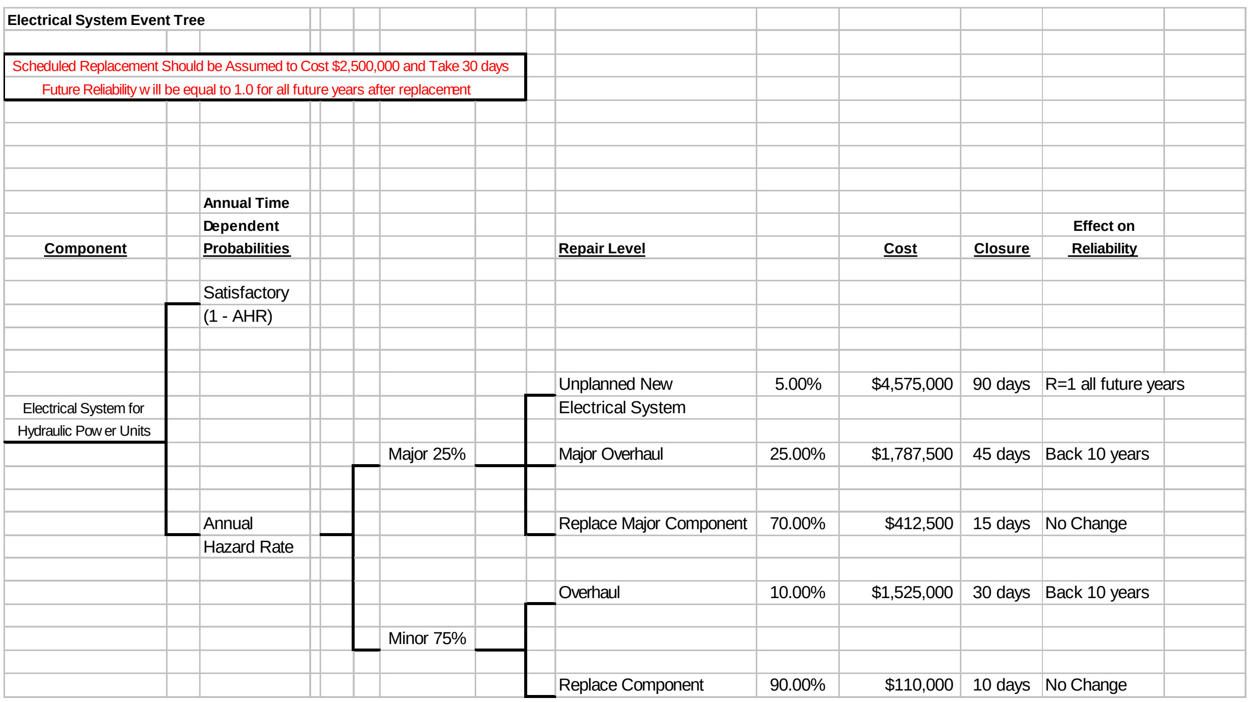


Figure 6.6.8.A. Electrical S ystem Event Tree

The cost breakdown for Major Failure/Unplanned New Electrical System is as follows:

New, unplanned electrical system →	$3,000,000
Specialty fleet at $17,500 for 90 days →	<u>$1,575,000</u>
Total for Unplanned, New Electrical →	$4,575,000

Because this is the least likely repair method, a 1.25% chance was assigned to this level. The 1.25% is derived from taking the 5% assigned to the branch multiplied by the 25% associated with the major failure branch. Future reliability of the electrical system once it is replaced is assumed to be 1.0 for the purposes of this study.

Major Failure, Major Overhaul of Electrical System. This assumes numerous failures to the electrical system such that an upgrade of several major components is required, but not a full replacement of the electrical system. Parts that are not replaced are assumed to be in good condition. An assumed closure time of 45 days was used for this repair level. Breakdown of cost and closure is detailed below.

Replacement parts for major overhaul	→	$1,000,000
Specialty fleet at $17,500 for 45 days	→	$ 787,500
Total for Major Repair Overhaul	→	$1,787,500

A 6.25% chance was assigned to this repair level by taking the 25% for the repair level multiplied by the 25% for the major failure branch. Therefore, it is assumed that this is not a likely repair scenario given a failure of the electrical system. With a major overhaul, not all parts are new, however, the major components would be new and thus, the reliability is assumed to be upgraded to what it was 10 years previous to the failure.

Major Failure, Replace Single Component. This assumes that only a single major component needs to be replaced and all others are in good condition. However, it is assumed replacing the component does not upgrade the overall reliability of the electrical system.

Cost of single major component	→	$150,000
Specialty fleet at $17,500 for 15 days	→	$262,500
Total to Replace Single Component	→	$412,500

This is considered to be the most likely repair level under the major failure branch of the event tree. A 17.5% chance was assigned to this repair by taking the 70% multiplied by the 25% for the major failure branch. As stated previously, reliability is not assumed to be upgraded for this repair.

Minor Failure Branch

There are two branches off of the minor failure portion of the event tree. These are a major overhaul of the electrical system and replacing a single component. An unplanned, new electrical system was left out of this branch since than can not be considered a minor failure. Each of these "minor" failures is detailed below.

Minor Failure, Overhaul of Electrical System. This assumes numerous failures to the electrical system such that an upgrade of several electrical components is required, but not a full replacement of the electrical system. Parts that are not replaced are assumed to be in good condition. The difference between this repair and the major overhaul for the major failure branch is the assumption that the diagnosis of the problem and repair time takes less time than under the other major failure branch. Therefore, only 30 days of chamber closure is required for this closure. Breakdown of cost and closure is detailed below.

Replacement parts for major overhaul	→	$1,000,000
Specialty fleet at $17,500 for 30 days	→	$ 525,000
Total for Major Repair Overhaul	→	$1,525,000

A 7.5% chance was assigned to this repair level by taking the 10% for the repair level multiplied by the 75% for the minor failure branch. With an overhaul, not all parts are new, however, the major components would be new and thus, the reliability is assumed to be upgraded to what it was 10 years previous to the failure. Again, with only 7.5% chance assigned to this branch, it is not considered a likely repair scenario.

Minor Failure, Replace Single Component. This assumes that only a single component needs to be replaced and all others are in good condition. However, it is assumed replacing the component does not upgrade the overall reliability of the electrical system. A chamber closure of 10 days is assumed for this repair, which includes the time for the specialty fleet to organize and get to the site. As opposed to the major failure branch, it is assumed that the single component is cheaper and a smaller crew would be required to install it for the minor failure branch.

Cost of single component →	$ 10,000
Specialty fleet at $10,000 for 10 days →	$100,000
Total to Replace Single Component →	$110,000

This is considered to be the most likely repair level in the entire event tree. A 67.5% chance was assigned to this repair by taking the 90% multiplied by the 75% for the minor failure branch. The reliability of the overall electrical system is not upgraded for this repair.

6.6.9 Hazard Rates and Calibration of Model

One of the first revisions required once the initial model was developed was to attempt and calibrate to a combination of historical performance at typical Ohio River lock projects and the engineering team's judgment. Immediately it was evident that several minor components were controlling the hazard rates in the results. These components were items such as fuses, switches, circuit breakers, relays, and solenoids. The team agreed that since these parts were easily replaceable and spares were readily available any chamber down time or repair cost would be insignificant in the overall economic analysis. Therefore, for the purposes of this study, it was assumed that all fuses, circuit breakers, switches, solenoids, and relays were 100% reliable so they did not affect the overall electrical system hazard rate.

As noted previously, the failure rates for the different components are pulled from data books for the electrical system. Therefore, the failure rates from the data books lead to an overall electrical system hazard rate that is much smoother when compared to the capacity versus demand hazard rates for structural components. The hazard rate for the main chamber electrical system at J.T. Myers is shown in Figure 6.6.9.A, whereas, the auxiliary chamber results are shown in Figure 6.6.9.B. The hazard rates for the both the main and auxiliary chamber electrical systems at Greenup are shown in Figure 6.6.9.C. As evidenced by these figures, the hazard rates for main and auxiliary chamber are only slightly different even though the operating cycles on the main chamber are considerably higher at both sites. This is due to the fact that the majority of the components in the system are operational all the time and not just when lockages occur. The panel board, wires for power and control, transformers, and commercial power are more a function of age because they are continually charged. The ages of the main and auxiliary chamber are essentially the same. Therefore, the difference between the two chambers is due to only two components, the controller and motor. These two components are a function of the number of operating cycles. The other components that are a function of the operating cycles were the minor components that were assumed 100% reliable because they were insignificant in terms of repair cost and chamber down time.

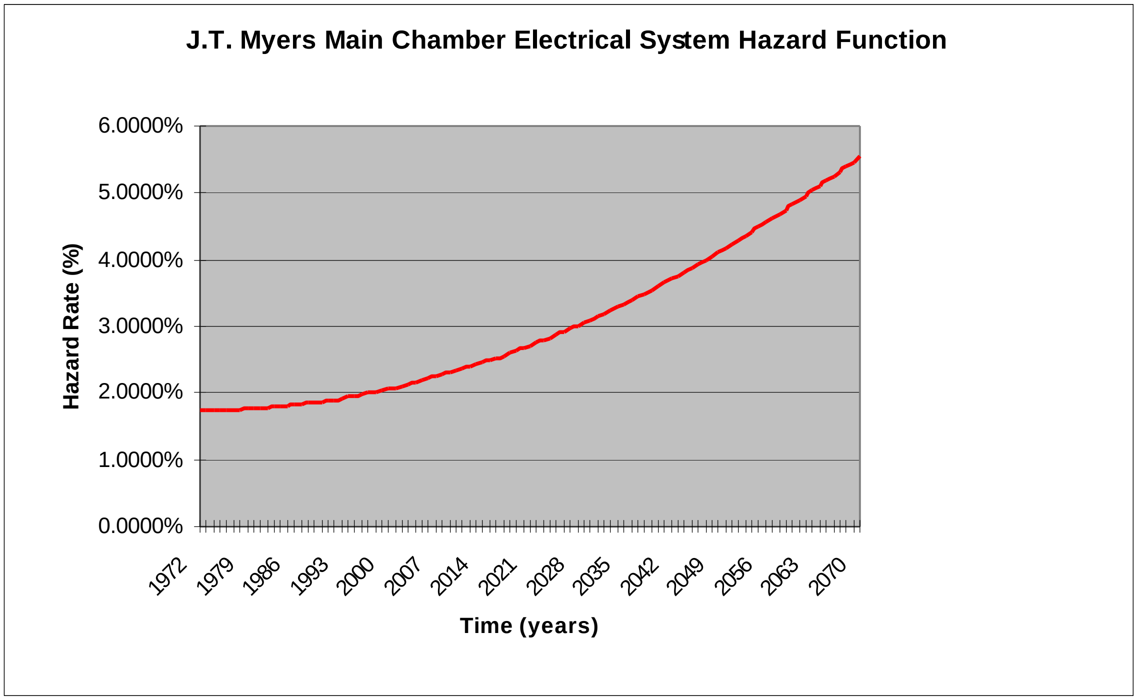


Figure 6.6.9.A. J.T. Myers Main Chamber Electrical System Hazard Rate

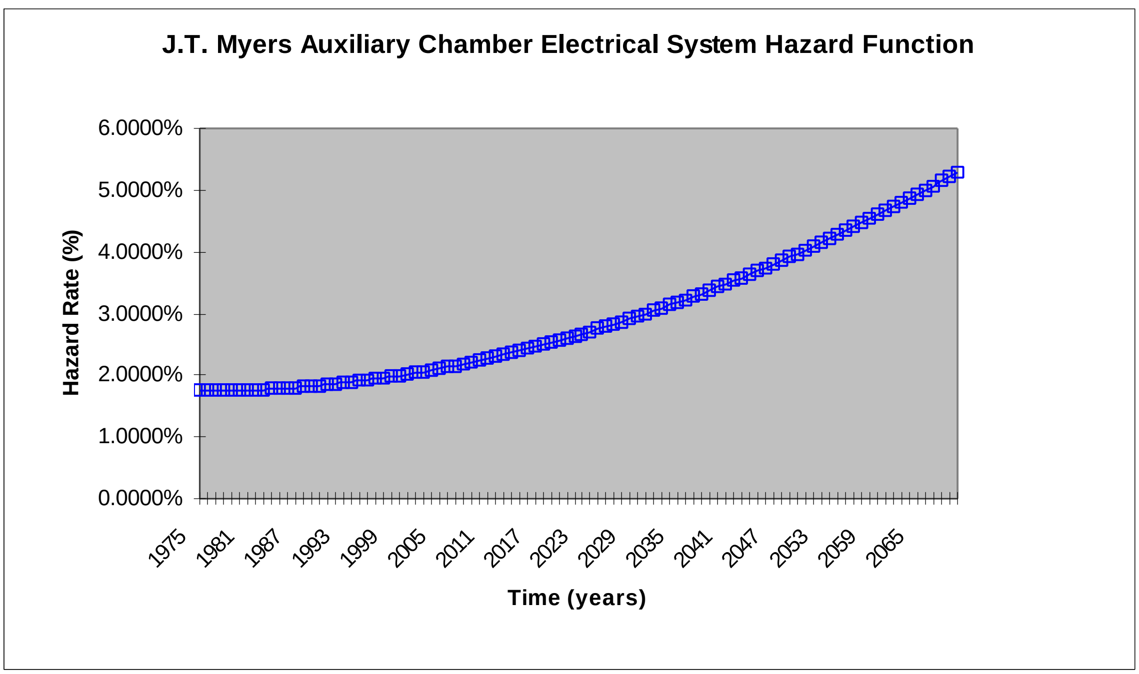


Figure 6.6.9.B. J.T. Myers Auxiliary Chamber Electrical System Hazard Rate

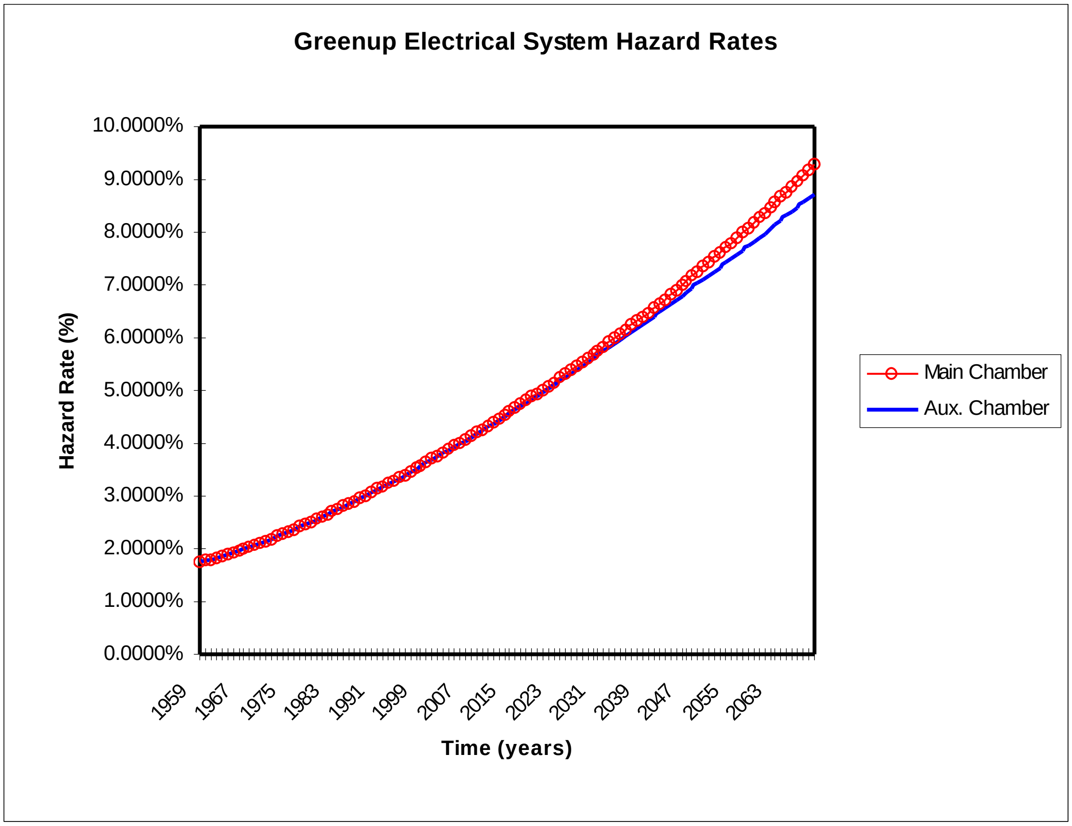


Figure 6.6.9.C. Greenup Electrical System Hazard Rates

6.6.10 Economic Analysis and Conclusions

The hazard rates shown in Figures 6.6.9.A through 6.6.9.C, along with the event tree shown in Figure 6.6.8.A, were provided to the economists to determine if a scheduled replacement of the electrical system is justified at both projects. Table 6.6.10.A shows the results of the economic analysis for both the main and auxiliary chamber electrical systems at both J.T. Myers and Greenup. As evidenced by the values in the table, the fix-as-fails alternative is the scenario with the lowest average annual cost for the main chamber at both sites. Although, a scheduled replacement of the main chamber electrical system is not justified independently at either site, this is not an indication there will never be problems associated with the main chamber electrical systems. It is just assumed that significant repairs will be done as part of normal, scheduled maintenance in the future. For the auxiliary chamber, scheduled replacements of the electrical systems at both the J.T. Myers and Greenup sites are economically justified around 2030. This is the year in which both sites had schedule replacements of the auxiliary chamber electrical system that yielded the lowest average annual cost of all scenarios. Therefore, projected closures of the auxiliary chambers at both the J.T. Myers and Greenup projects were placed in the cost and closure matrices for the overall economic analysis. The closures that were placed in the matrices matched the 30 days and $2.5 million cost as found in the event tree in Figure 6.6.8.A for a scheduled replacement. The large cost difference between the main and auxiliary chamber is mainly a function of the navigation delay costs associated with the main chamber. If the main chamber is closed for any reason (including "failure" of the electrical system as outlined in the event tree), then large navigation delays quickly add up since the tows now have to double cut through the smaller auxiliary chamber. Thus, the fix-as-fails alternative at J.T. Myers is roughly 10 times more for the main chamber as compared to the auxiliary chamber. Likewise, the 30 day scheduled closure to replace the electrical system has a large impact as well when projecting those closures into the economic analysis in select years.

Table 6.6.10.A. Economic Analysis of Electrical Systems at J.T. Myers and Greenup

Average Annual Costs for J.T. Myers and Greenup Electrical System			
Description of Scenario for Economic Analysis	Lock Chamber	J.T. Myers Average Annual Cost	Greenup Average Annual Cost
Fix-as-Fails	**Main**	**$904,500**	**$903,200**
Replace in 2010	Main	$1,664,200	$1,229,200
Replace in 2020	Main	$1,398,500	$1,130,100
Replace in 2030	Main	$1,209,900	$1,048,400
Replace in 2040	Main	$1,304,100	$1,083,100
Fix-as-Fails	Auxiliary	$99,600	$227,600
Replace in 2000	Auxiliary	$408,800	$397,100
Replace in 2010	Auxiliary	$227,200	$258,100
Replace in 2020	Auxiliary	$145,400	$207,300
Replace in 2030	**Auxiliary**	**$98,000**	**$194,900**
Replace in 2040	Auxiliary	$102,200	$207,300

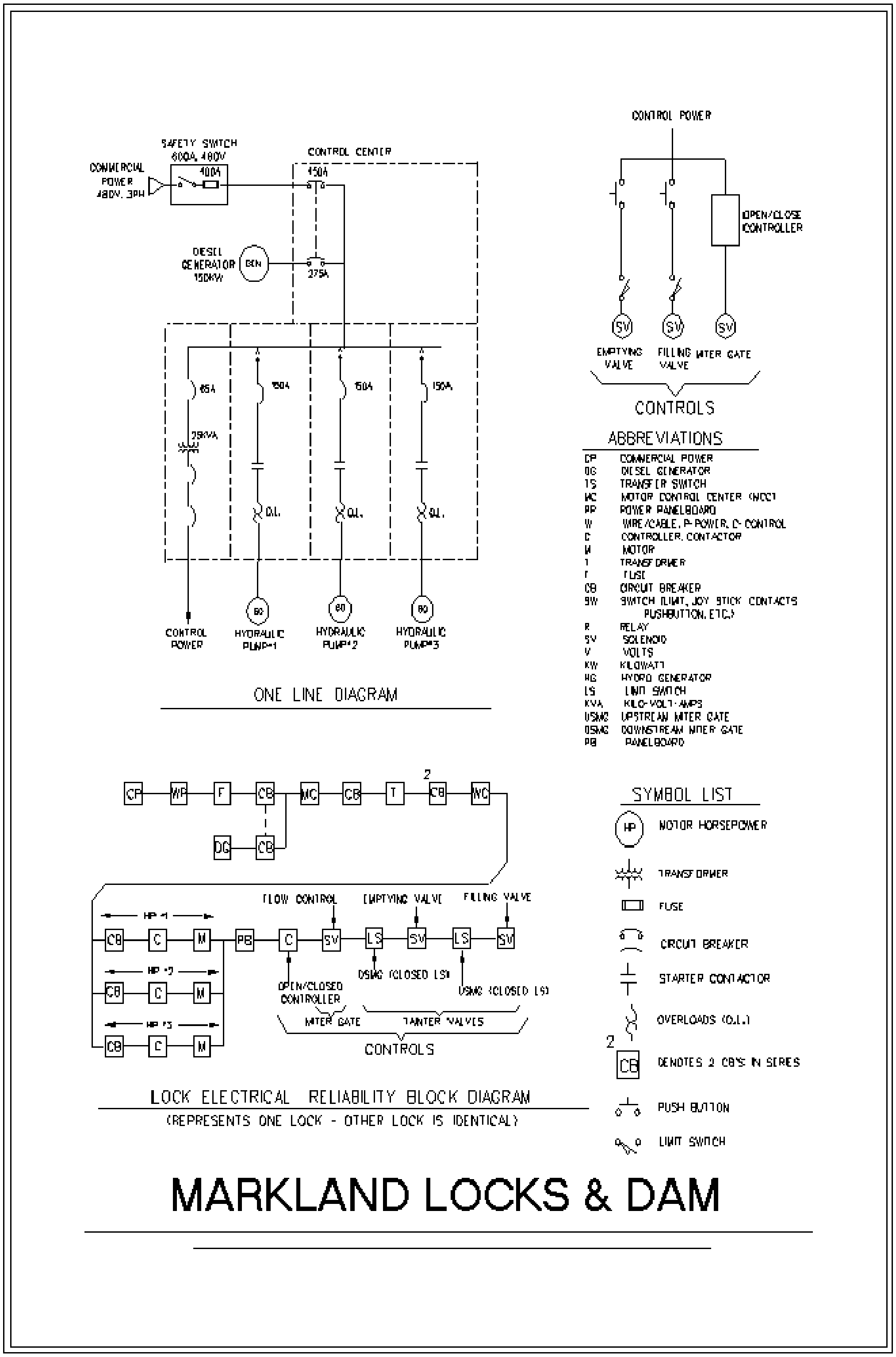


Figure 6.6.3.A. Electrical One-Line Diagram for Typical ORMSS Project

Duty Cycle				Com.Power	Diesel Genset	X-fer Switch	MCC	Panel Board	Wire,power	Wire,control	Controller	Motor	Xfmr,power	Xfmr,lv	Fuse
	Avg. # of open/close cycles per yr.			NA	NA	NA	NA	NA	NA	NA	7194	7194	NA	NA	7194
	time for open/close cycle, sec			NA	NA	NA	NA	NA	NA	NA	1200	1200	NA	NA	1200
	Avg. operating time, hrs. per year			8760	36	8760	8760	8760	8760	8760	2398.141	2398.141	8760	8760	2398.141
	Mission time, t, years			98	98	98	98	98	98	98	98	98	98	98	98
	Mission time, t, 1E6 hrs.			0.85848	0.85848	0.85848	0.85848	0.85848	0.85848	0.85848	0.85848	0.85848	0.85848	0.85848	0.85848
	d, duty factor			100.00%	0.41%	100.00%	100.00%	100.00%	100.00%	100.00%	27.38%	27.38%	100.00%	100.00%	27.38%
Failure Rate															
	Lambda, L, failures/1E6 oper.hrs.			0.019	7.65	4.55	3	3	1	1	3	10	1	1	12.1
	(Yrs. To failure)			6008.17	3631.08	25.09	38.05	38.05	114.16	114.16	139.00	41.70	114.16	114.16	34.46
	Value for L=C if life calc,D if data			D	D	D	D	D	D	D	C	C	D	D	C
	MTTF = 1/L , E6hrs.			52.63158	0.13072	0.21978	0.33333	0.33333	1.00000	1.00000	0.33333	0.10000	1.00000	1.00000	0.08264
	Beta			1	1	1	2.5	2.5	1	1	2.5	2.5	1	1	1
	Alpha=MTTF*Beta, E6 hrs.			52.63158	0.13072	0.21978	0.83333	0.83333	1.00000	1.00000	0.83333	0.25000	1.00000	1.00000	0.08264
	Alpha, yrs.			6008.17	14.92	25.09	95.13	95.13	114.16	114.16	95.13	28.54	114.16	114.16	9.43
Weibull Reliability Function															
	R(t)=exp[-(td/Alpha)**Beta]			98.38%	97.34%	100.00%	34.06%	34.06%	42.38%	42.38%	95.86%	42.45%	42.38%	42.38%	100.00%
	(at t = 50)														
	(at t = 1)			99.98%	99.97%	100.00%	100.00%	100.00%	99.13%	99.13%	100.00%	100.00%	99.13%	99.13%	100.00%
	Year Completed -		1971												
	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986
Project Age	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Com.Power	99.98%	99.97%	99.95%	99.93%	99.92%	99.90%	99.88%	99.87%	99.85%	99.83%	99.82%	99.80%	99.78%	99.77%	99.75%
---age, yrs.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Diesel Genset	99.97%	99.94%	99.92%	99.89%	99.86%	99.83%	99.81%	99.78%	99.75%	99.72%	99.70%	99.67%	99.64%	99.62%	99.59%
---age, yrs.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
X-fer Switch	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
---age, yrs.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
MCC	100.00%	99.99%	99.98%	99.96%	99.94%	99.90%	99.85%	99.80%	99.73%	99.64%	99.55%	99.44%	99.31%	99.17%	99.02%
---age, yrs.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Panel Board	100.00%	99.99%	99.98%	99.96%	99.94%	99.90%	99.85%	99.80%	99.73%	99.64%	99.55%	99.44%	99.31%	99.17%	99.02%
---age, yrs.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Wire,power	99.13%	98.26%	97.41%	96.56%	95.71%	94.88%	94.05%	93.23%	92.42%	91.61%	90.81%	90.02%	89.24%	88.46%	87.69%
---age, yrs.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Wire,control	99.13%	98.26%	97.41%	96.56%	95.71%	94.88%	94.05%	93.23%	92.42%	91.61%	90.81%	90.02%	89.24%	88.46%	87.69%
---age, yrs.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Controller	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	99.99%	99.99%	99.99%	99.99%	99.98%	99.98%	99.97%	99.97%	99.96%
---age, yrs.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Motor	100.00%	99.99%	99.99%	99.97%	99.95%	99.92%	99.88%	99.84%	99.78%	99.72%	99.64%	99.55%	99.45%	99.34%	99.22%
---age, yrs.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Xfmr,power	99.13%	98.26%	97.41%	96.56%	95.71%	94.88%	94.05%	93.23%	92.42%	91.61%	90.81%	90.02%	89.24%	88.46%	87.69%
---age, yrs.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Xfmr,lv	99.13%	98.26%	97.41%	96.56%	95.71%	94.88%	94.05%	93.23%	92.42%	91.61%	90.81%	90.02%	89.24%	88.46%	87.69%
---age, yrs.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Fuse	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
---age, yrs.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Circuit Bkr.	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
---age, yrs.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Switch	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
---age, yrs.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Relay	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
---age, yrs.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Solenoid	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
---age, yrs.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15

Figure 6.6.5.A Example Reliability Model Computations for J.T. Myers Main Chamber Lock Electrical System

6.7 MECHANICAL SYSTEM RELIABILITY FOR THE LOCK

The mechanical systems for the lock essentially are made up of three major components: miter gate machinery, culvert valve machinery, and the supporting hydraulic system. Because each of these components has different failure conditions and subsequent repairs with differing consequences, each component was independently tracked in the overall mechanical model. Therefore, hazard rates and separate event trees were developed for each of the three components in both chambers. Due to schedule and funding constraints, only the mechanical system results for J.T. Myers and Greenup were totally completed (runs calibrated, through ITR, etc.) at the time of this interim report. Therefore, this section will only detail the results for these two sites. The reliability assessments of all other Ohio River projects will be completed as part of the overall ORMSS final report. The reliability results for the mechanical systems at J.T. Myers and Greenup will also be carried forward into the final ORMSS report.

6.7.1 Assessment of Reliability for Mechanical System

The mechanical reliability assessment is based on procedures defined by ETL 1110-2-549, Engineering and Design, RELIABILITY ANALYSIS OF NAVIGATIONAL LOCK AND DAM MECHANICAL AND ELECTRICAL EQUIPMENT, 30 Nov 1997. The following paragraphs document the assumptions, current conditions and provide the results of the reliability assessment.

6.7.2 Component Condition Investigations

Both the J.T. Myers and Greenup projects have two lock chambers. The main chamber for each site is 110 feet wide by 1,200 feet long. The auxiliary chamber at each site is 110 feet wide by 600 feet long. The main chamber has an upper and lower set of miter gates and two filling and two emptying reverse tainter gate style culvert valves. The auxiliary chamber has a upper and lower set of miter gates and one filling and one emptying reverse tainter gate style culvert valve. Each miter gate and culvert valve is operated by a hydraulic cylinder connected to a central pump system. Three main pumps and one small pump operate the hydraulic system for the entire locks. The lock machinery at both projects is the original equipment installed when the project was completed. Greenup commenced locking operations in 1959. J.T. Myers commenced locking operations in 1972. Periodic inspections and review of the original lock design drawings were conducted to assist in finding the current condition of the mechanical systems.

6.7.3 Selected Limit States for the Mechanical System

The probability of unsatisfactory performance (PUP) was computed from time of installment through the year 2070. An additional 10 years was added to the study period for the reliability models in the event they were needed for the economic analysis. It was computed in increments of years between these times to provide a trend of unsatisfactory performance. The limit state was defined as the "meanlife" or Mean Time To Failure (MTTF) of the components analyzed.

6.7.4 Lock Mechanical Systems and Subsystems Analyzed

For this analysis, each of the four mechanical gate systems and each of the valve systems were considered separate models. The lock miter gate machinery is the same for J.T. Myers and Greenup. The diagram is shown in Figure 6.7.4.A. The valve machinery systems for the two projects are slightly different. The J.T. Myers and Greenup valve machinery systems are shown in Figures 6.7.4.B and 6.7.4.C, respectively. The hydraulic system line diagrams for the J.T. Myers and Greenup projects are shown in Figures 6.7.4.D, 6.7.4.E, and 6.7.4.F in the back of Section 6.7.

6.7.5 Reliability Block Diagram Formulation

This analysis and the formulation of the system reliability block diagrams (RBD) are in accordance with ETL 1110-2-549. The machinery functions to operate the miter gates and reverse tainter culvert valves. The major components required for mission success are defined and organized into an RBD. For the miter gate subsystems for the main chamber, if one component does not function, then the entire system for that chamber will not function. On the auxiliary chamber, if one of the culvert valves or miter gate systems does not operate then the entire system will not function. There are no parallel or redundant items, therefore, the mission and basic block diagrams are arranged as series system models. The block diagrams for the miter gate components at J.T. Myers and Greenup are shown in Figure 6.7.4.A. The culvert valve components included in this evaluation are shown in Figures 6.7.4.B (J.T. Myers) and Figure 6.7.4.C (Greenup). In this analysis, the structural supports and anchorages are not included in the model. They are unique to the system and there is no published failure rate data available.

6.7.6 Subsystem Reliability Calculation

a. Duty Cycle. The miter gate equipment was considered to have a negligible failure rate during periods of non-operation (ignoring barge impact). The failure rate can be modified by a duty cycle factor. The duty cycle factor is the ratio of actual operating time to total mission time, t. The lock equipment operates a certain number of open/close cycles per year. Please reference the historic and projected cycles for both chambers at J.T. Myers and Greenup in horizontally-framed miter gate section.

(1) J.T. Myers Main Chamber Duty Cycle. The average number of open/close cycles for the main chamber is 7,237 and assuming the operating time of (189 seconds per open/close cycle), and using a total mission time of 98 years, then,

Operating time = (189*7,237)/3600
= 380 operational hrs per year * 98 yrs
= 37,240 hours = 4.2511 years

For t = 98 years (1972 through 2070),
d = 4.2511/98 = 0.0434

The same process is used to determine the duty cycle for the auxiliary chamber by using the appropriate values for the auxiliary chamber at J.T. Myers.

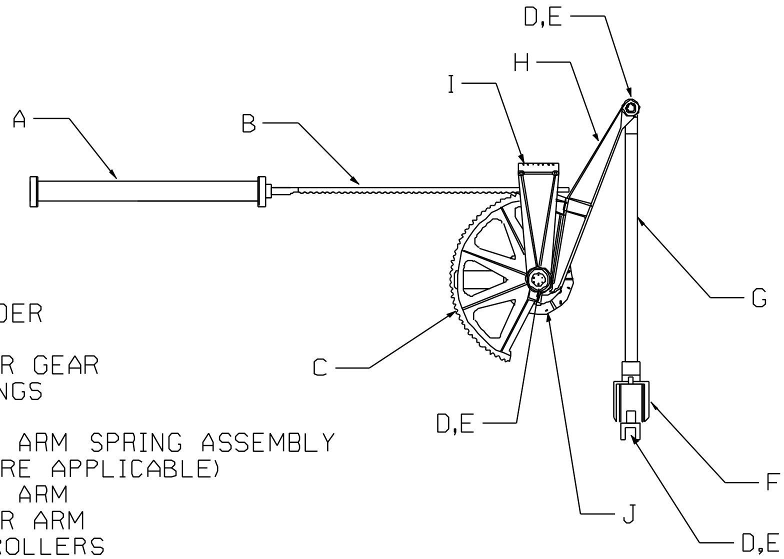
(2) Greenup Main Chamber Duty Cycle. The average number of open/close cycles for the main chamber is 5,473 and assuming the operating time of (240 seconds per open/close cycle), and using a total mission time of 111 years, then,

Operating time = (240*5,473)/3600
= 365 operational hrs per year * 111 yrs
= 40,500 hours = 4.623 years

For t = 111 years (1959 through 2070),
d = 4.623/111 = 0.0416

The same process is used to determine the duty cycle for the auxiliary chamber by using the appropriate values for the auxiliary chamber at Greenup.

b. Environmental Conditions. The environmental conditions were defined for the ambient service of the lock equipment as an outdoor marine environment. The environmental K factors were selected from Table C-l of ETL 1110-2-549. For this analysis, a Kl factor of 2 is used and K2 and K3 are 1.0.



A = CYLINDER
B = RACK
C = SECTOR GEAR
D = BEARINGS
E = PINS
F = STRUT ARM SPRING ASSEMBLY
(WHERE APPLICABLE)
G = STRUT ARM
H = SECTOR ARM
I = RACK ROLLERS
J = SECTOR BASE

A — B — C — D — E — D — E — F — D — E

ITEMS NOT EVALUATED DUE TO LIMITED FAILURE RATE INFORMATION:

SECTOR ARM
STRUT ARM
SECTOR BASE

ITEMS DETERMINED UNNECESSARY FOR RELIABILITY ANALYSIS:

RACK ROLLERS
VARIOUS NUTS AND BOLTS

OHIO RIVER MAINSTEM SYSTEM STUDY MECHANICAL SYSTEMS RELIABILITY BLOCK DIAGRAM	MYERS LOCKS MITER GATE MACHINERY

Figure 6.7.4.A. J.T. Myers and Greenup Miter Gate Machi nery System

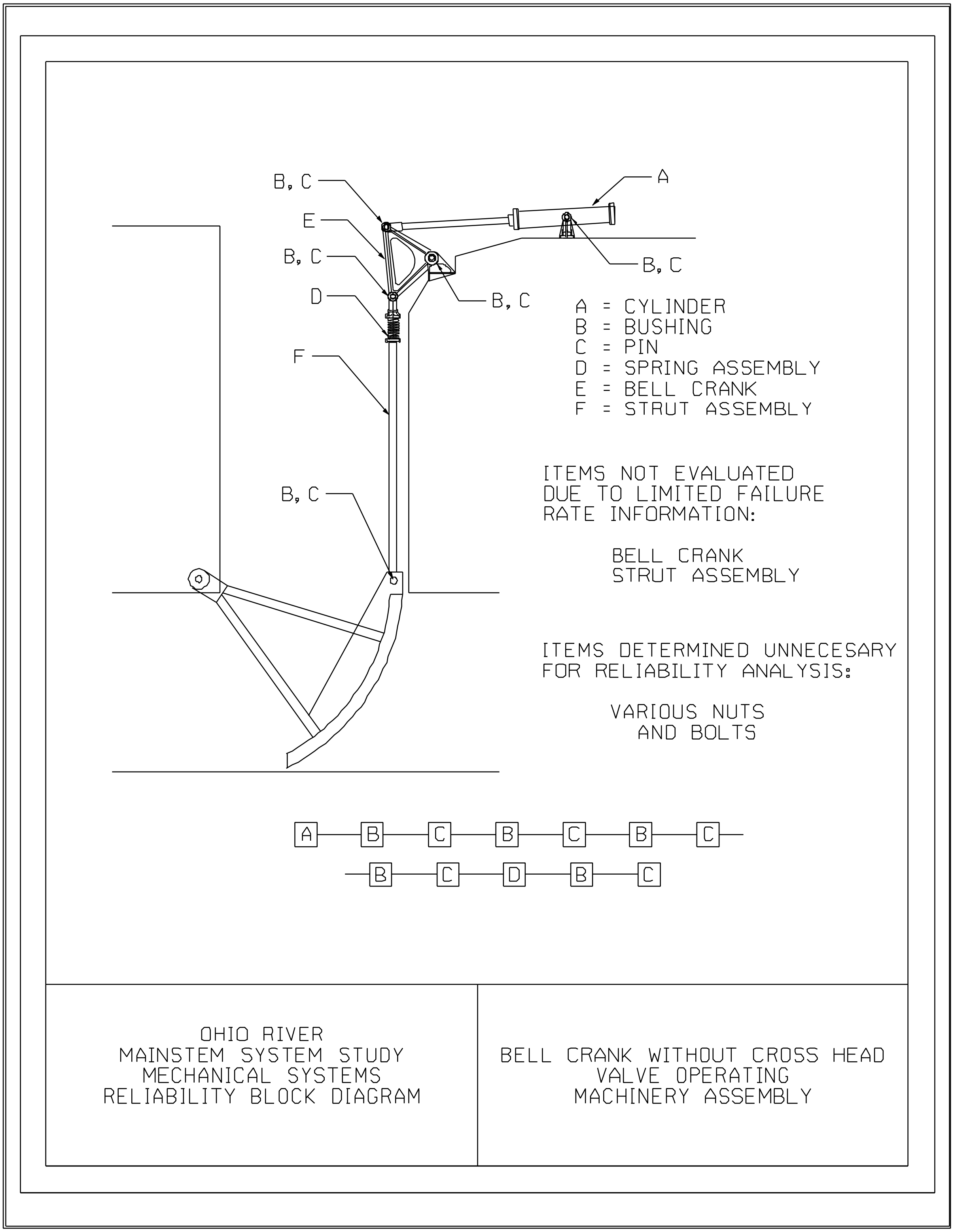


Figure 6.7.4.B. J.T. Myers Culvert Valve Machinery System

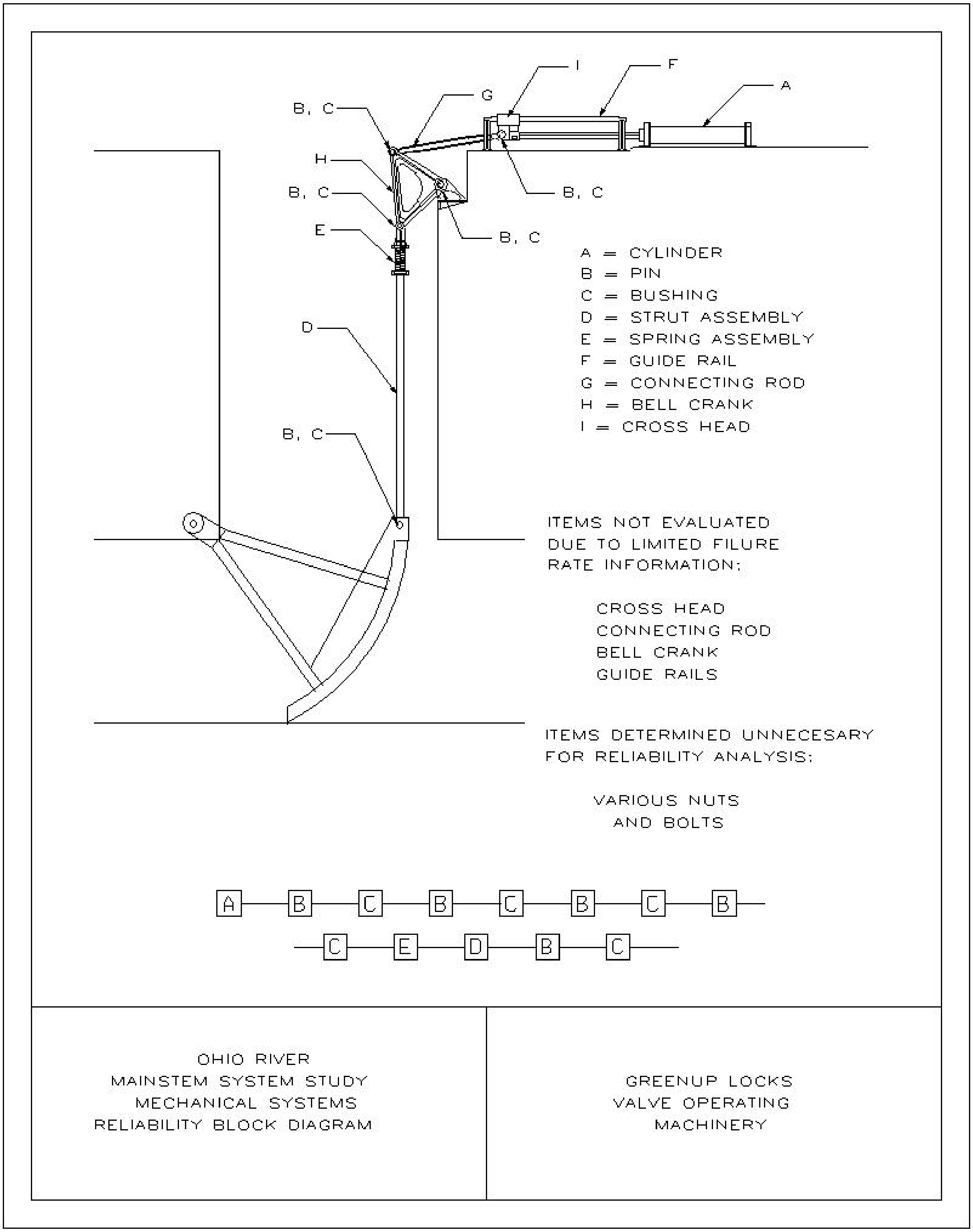


Figure 6.7.4.C. Greenup Culvert Valve Machinery System

c. Lock Equipment Reliability. The Weibull distribution was used to perform the reliability analysis for each component in the block diagram. The shape parameter values for b were selected from the values given in Table C-6 of the ETL, by choosing a dominant failure mode for each component. The characteristic life parameter *a* was determined from the failure rate data using the methods presented in the ETL. The failure rates for the lock mechanical components were selected from Table C-7 of the ETL. These failure rates were multiplied by the K factor to obtain a final adjusted failure rate. The parameter *alpha* was determined as follows:

$$\alpha = \frac{\gamma}{\lambda}$$

Where,

γ = (α/MTTF ratio from Table C-2 of ETL 1110-2-549)

λ = Adjusted failure rate = SK

The Weibull reliability function for the components becomes:

$R(t) = \exp[-(td/\alpha)^{\beta}]$ where t is in years

Miter Gate:

Where the shape parameter (b) is equal to 1.0, the Weibull distribution reduces to the Exponential distribution. The miter gate mechanical subsystem was considered to begin at the first gearset. The subsystem reliability at both projects for the miter gate machinery model in Figure 6.7.4.A at time *t* is determined from the individual reliability of each component as follows:

$$R_{MGMachinery}(t) = R_A(t) * R_B(t) * R_C(t) * R_D(t)^3 * R_E(t)^3 * R_F(t)$$

Where,

$R_A(t)$ = Reliability of the cylinder

$R_B(t)$ = Reliability of the rack

$R_C(t)$ = Reliability of the sector gear

$R_D(t)$ = Reliability of the bearings

$R_E(t)$ = Reliability of the pins

$R_F(t)$ = Reliability of the strut arm spring assembly

Culvert Valve:

J.T. Myers Culvert Valve Machinery. The culvert valve mechanical subsystem was considered to begin at the first coupling. The subsystem reliability for the culvert valve machinery model at J.T. Myers (See Figure 6.7.4.B) is calculated as:

$$R_{MyersCVMachinery}(t) = R_A(t) * R_B(t)^5 * R_C(t)^5 * R_D(t)$$

Where,

$R_A(t)$ = Reliability of the cylinder

$R_B(t)$ = Reliability of the bushing

$R_C(t)$ = Reliability of the pin

$R_D(t)$ = Reliability of the spring assembly

Greenup Culvert Valve Machinery. The subsystem reliability for the culvert valve machinery model at Greenup, as shown in Figure 6.7.4.C, is calculated as:

$R_{GrnpCVMachinery}(t) = R_A(t) * R_B(t)^5 * R_C(t)^5 * R_D(t) * R_E(t)$

Where,
$R_A(t)$ = Reliability of the cylinder
$R_B(t)$ = Reliability of the pin
$R_C(t)$ = Reliability of the bushing
$R_D(t)$ = Reliability of the strut assembly
$R_E(t)$ = Reliability of the spring assembly

Hydraulic Subsystems:

J.T. Myers Overall Hydraulic System (See Figure 6.7.4.D in back of this section)

$R_{HYDRAULIC}(t) = R_{PUMP}(t) * R_{PIPE}(t) * R_{CVHYDR}(t) * R_{MGHYDR}(t)$

J.T. Myers Pump Room Hydraulic System Reliability

$R_{PUMP}(t) = R_C(t) * R_J(t) * [1 - (1 - (R_C(t)^2 * R_F(t) * (1 - (1 - R_B(t))(1 - R_J(t)))))]*[1 - (1 - R_C(t))^2]$

Where,
$R_C(t)$ = Reliability of shutoff valve
$R_J(t)$ = Reliability of filters/strainer
$R_F(t)$ = Reliability of pump
$R_B(t)$ = Reliability of check valve

J.T. Myers Culvert Valve Machinery Hydraulic System Reliability

$R_{CVHYDR}(t) = [1 – (1 - R_C^3)(1- R_C*R_G)] * R_C * [1 – (1 – R_{L1})(1 – R_{L2})(1 – R_{L3})]$

Where,
$R_C(t)$ = Reliability of shutoff valve
$R_G(t)$ = Reliability of manual control valve
$R_J(t)$ = Reliability of filters/strainer
$R_H(t)$ = Reliability of solenoid control valve
$R_I(t)$ = Reliability of flow control valve
$R_B(t)$ = Reliability of check valve
$R_K(t)$ = Reliability of the cylinder
$R_{L1} = R_C(t)^2 * R_J(t)$
$R_{L2} = R_H(t)^2 * R_C(t) * [1 – (1 – R_I(t))(1 – R_B(t)))]$
$R_{L3} = R_B(t) * R_H(t) * R_D(t)^2 * R_I(t)^2 * R_K(t) * R_C(t)^4$

J.T. Myers Miter Gate Hydraulic System Reliability

$R_{MGHYDR}(t) = R_I * R_C * [1 – (1 – R_C^2*R_G)^2] * [1 – (1 – R_K)(1 – R_B^2)(1 – R_D^2)] * [1 – (1 – R_I)^2]$

Where,
$R_C(t)$ = Reliability of shutoff valve
$R_G(t)$ = Reliability of manual control valve
$R_I(t)$ = Reliability of flow control valve
$R_B(t)$ = Reliability of check valve
$R_K(t)$ = Reliability of the cylinder
$R_D(t)$ = Reliability of relief valve

Greenup Overall Hydraulic System (See Figure 6.7.4.E in back of this section)

$$R_{HYDRAULIC}(t) = R_{PUMP}(t) * R_{PIPE}(t) * R_{CVHYDR}(t) * R_{MGHYDR}(t)$$

Greenup Pump Room Hydraulic System Reliability

$$R_{PUMP}(t) = R_D(t)^2 * R_C(t) * [1 - \{1 - R_F(t) * R_A(t) * R_D(t) * R_B(t) * R_C(t)\}^3]$$

Where,
$R_A(t)$ = Reliability of coupling
$R_B(t)$ = Reliability of check valve
$R_C(t)$ = Reliability of shutoff valve
$R_D(t)$ = Reliability of relief valve
$R_F(t)$ = Reliability of flow pump

Greenup Culvert Valve Machinery Hydraulic System Reliability

$$R_{CVHYDR}(t) = R_C(t)^9 * R_G(t)^4$$

Where,
$R_C(t)$ = Reliability of shutoff valve
$R_G(t)$ = Reliability of control valve

Greenup Miter Gate Machinery Hydraulic System Reliability

$$R_{MGHYDR}(t) = R_C(t)^7 * R_B(t)^2 * R_D(t)^2 * R_G(t)^3$$

Where,
$R_B(t)$ = Reliability of check valve
$R_C(t)$ = Reliability of shutoff valve
$R_D(t)$ = Reliability of relief valve
$R_G(t)$ = Reliability of control valve

6.7.7 Hazard Calculation for the Mechanical System

The Weibull hazard function was used to determine the hazard rate of each component. The Weibull hazard function is:

$$h(t) = \frac{\beta\,[td]^{\beta-1}}{(\alpha)(\alpha)}$$

The subsystem hazard rates for the miter gate and culvert valve models were calculated from the hazard rates of the individual components using the following relationship:

$$h_{subsys}(t) = \sum h_i(t)$$

Where,

$h_i(t)$ = Hazard rate for the individual components
$i = 1,n$

6.7.8 Mechanical System Event Trees

For the economic analysis, the overall mechanical system model was broken into three separate components: miter gate machinery, culvert valve machinery, and the hydraulic system. This was necessary for the development of separate event trees for each component. Additionally, in calibrating the model, the repair history may be different for each of the different components. Therefore, each component was analyzed individually for the purposes of this study. Costs and closures associated with different levels for repair are provided in the event tree along with the effect on future reliability based upon the type of repair. Another piece of information in the event tree is the cost and closure associated with replacing the component ahead of failure on a scheduled basis. This information is used to determine not only if it is more economical to replace the component ahead of failure, but also assists in timing the replacement of the component.

The event trees for the culvert valve machinery and hydraulic system are further divided into the main and auxiliary chambers. Since the miter gate machinery for the main and auxiliary chamber is the same at each project, one event tree was sufficient for that component.

Miter Gate Machinery Event Tree

The event tree for the miter gate machinery of the main and auxiliary chamber is shown in Figure 6.7.8.A. There are two levels of repair assumed, one for major repairs and one for minor repairs. A break down of the costs and closures associated with the miter gate machinery event tree is provided below.

Miter Gate Machinery Major Failure, Unplanned New Miter Gate Machinery. This repair level assumes a catastrophic failure of the miter gate machinery where it is not repairable. New machinery needs to be fabricated and installed. Closure time assumes 90 days at a cost of $6,588,000. A break down of the cost is supplied below.

New miter gate machinery parts → $3,438,000

Repair fleet for 90 days on-site at \$35,000 per day → \$3,150,000
Total for unplanned miter gate machinery repair → \$6,588,000

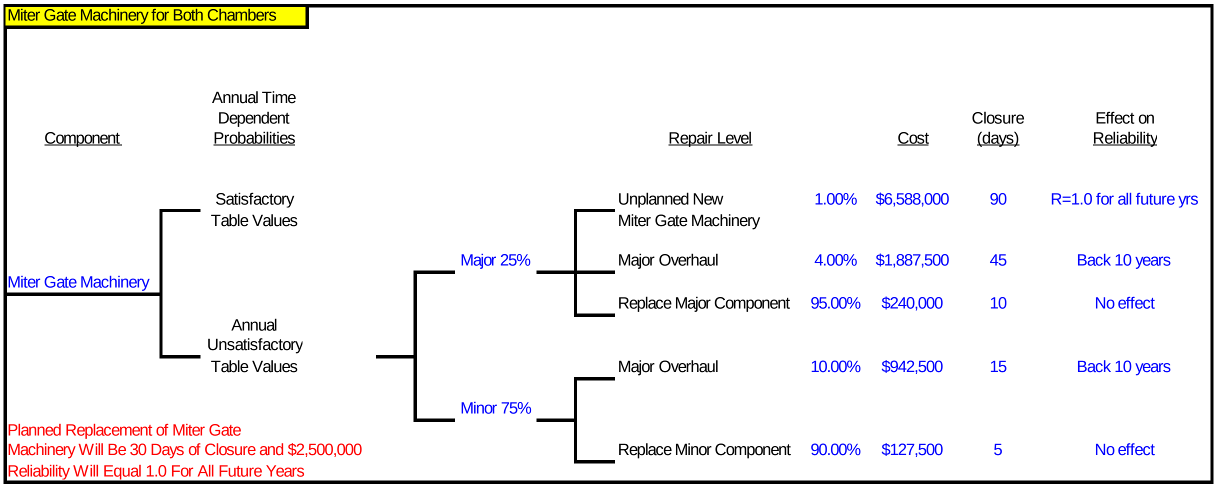


Figure 6.7.8.A. Miter Gate Machinery Event Tree

This repair level is assumed to be the least likely of all the options. A 0.25% chance of occurrence was assigned to this repair level. The 0.25% is calculated by taking the 25% associated with the major failure branch and multiplying to the 1% assigned to the unplanned miter gate machinery repair level. With a new machinery system, an updated reliability of 1.0 is assigned for the rest of the study period.

Miter Gate Machinery Major Failure, Major Overhaul to Miter Gate Machinery. This repair level assumes a major failure to the miter gate machinery, however, the only repair to the machinery is to install several new, large components. Closure time assumed is 45 days at a cost of \$1,887,500.

Major overhaul miter gate machinery parts → \$1,100,000
Smaller repair fleet on-site for 45 days at \$17,500/day → \$ 787,500
Total for major failure, major overhaul repair → \$1,887,500

This repair level is assumed to occur 1% of the time. Again, this value is obtained by multiplying 25% for major failure by 4% assigned to this repair level. This is not seen as a likely repair scenario, but it is possible. Since not all of the machinery would be new, the future reliability is assumed to improve but not to the level of a new system. It is assumed the reliability is pushed back to what the value was 10 years previous.

Miter Gate Machinery Major Failure, Replace Single Component. This repair level is assumed to be most likely for any type of major failure. An overall 23.75% is assigned to this repair level. This assumes only one major component needs to be replaced due to the failure. The future reliability is assumed to be unaffected. The cost break down for this repair is shown below.

Replace major component parts → \$ 65,000
Smaller repair fleet on-site for 10 days at \$17,500/day → \$175,000
Total for major failure, replace major component → \$240,000

Miter Gate Machinery Minor Failure, Major Overhaul of Miter Gate Machinery. This repair level assumes a failure to the miter gate machinery, however, the repair the machinery is to install several smaller, new components. Closure time assumed is 15 days at a cost of $262,500.

Major overhaul miter gate machinery parts →	$680,000
Smaller repair fleet on-site for 15 days at $17,500/day →	<u>$262,500</u>
Total for minor failure, major overhaul repair →	$942,500

This repair level is assumed to occur 7.5% of the time. Again, this value is obtained by multiplying 75% for minor failure by 10% assigned to this repair level. It is assumed the reliability is pushed back to what the value was 10 years previous.

Miter Gate Machinery Minor Failure, Replace Minor Component. The most likely repair level assumed is for the replacement of a minor component. A 67.5% level was assigned to this repair. The cost is estimated at $127,500 and a closure time of only 5 days. The cost for the new component is estimated at $40,000 and the remaining cost is for the small repair fleet on-site for 5 days at $17,500 per day. Because only a single component is being replaced, it is assumed that the overall reliability associated with the miter gate machinery is not improved.

Culvert Valve Machinery Event Trees

The event trees associated with the culvert valve machinery must be broken into two separate event trees since there are four valves on the main chamber and only two on the auxiliary chamber. Because there are two filling and emptying valves a piece for the main chamber, it can be operated at half-speed if one valve machinery fails. Since there is only a single filling and emptying valve for the auxiliary chamber, any malfunction of the valve machinery for the auxiliary chamber causes it to close. The main and auxiliary culvert valve machinery event trees are shown in Figures 6.7.8.A and 6.7.8.B, respectively. The event trees are the same for both chambers with the exception of the costs associated with only having two valves for the auxiliary and the ability to operate the main chamber at half-speed.

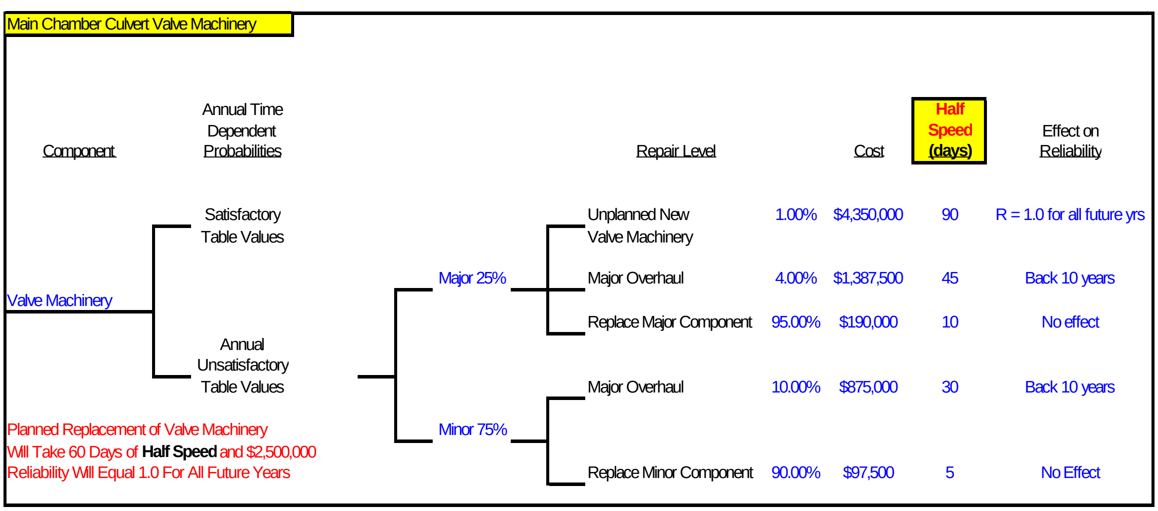


Figure 6.7.8.A. Main Chamber Culvert Valve Machinery Event Tree

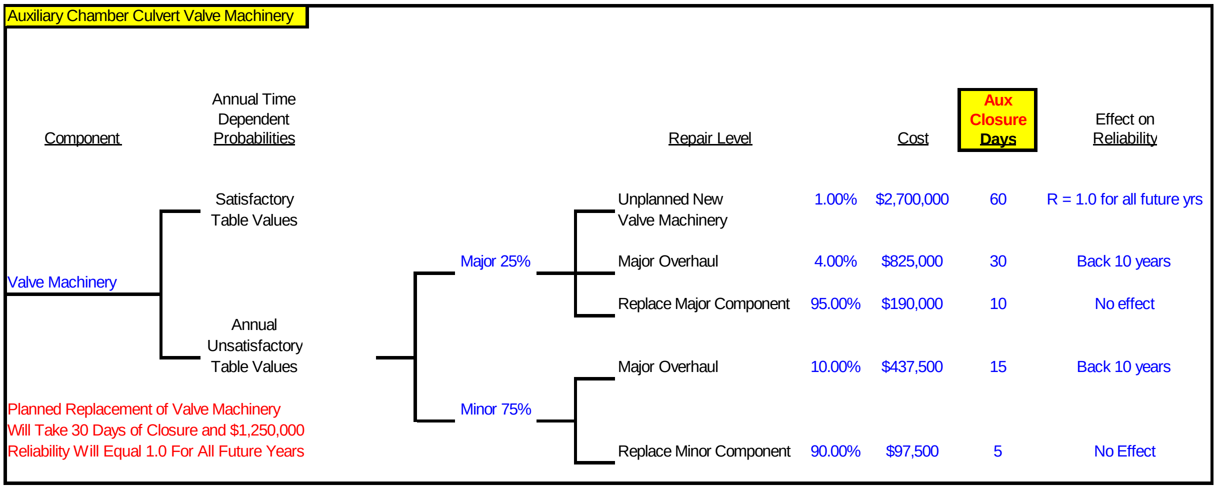


Figure 6.7.8.B. Auxiliary Chamber Culvert Valve Machinery Event Tree

Culvert Valve Machinery Major Failure, Unplanned New Valve Machinery. Similar to the miter gate machinery, this assumes a catastrophic failure to one of the culvert valve machinery sets. Repair time is estimated to be 90 days for the main chamber and 60 days for the auxiliary chamber. The main chamber would operate at half speed during that time, while the auxiliary chamber would be closed. Only 0.25% is assigned to this repair level for both chambers. Future reliability is assumed to 1.0 after the new machinery is installed for all culvert valves. A break down of the costs for the main chamber and auxiliary chambers is supplied below.

Main chamber unplanned new valve machinery, 4 sets →	$1,200,000
Full repair fleet on-site 90 days at $35,000 per day →	<u>$3,150,000</u>
Total for main chamber, valve machinery →	$4,350,000
Auxiliary chamber, unplanned new valve mach., 2 sets →	$ 600,000
Full repair fleet on-site 60 days at $35,000 per day →	<u>$2,100,000</u>
Total for auxiliary chamber, valve machinery →	$2,700,000

Culvert Valve Machinery Major Failure, Major Overhaul of Valve Machinery. This assumes a major failure to the culvert valve machinery, however, the valve machinery can be made serviceable again. Closure time for auxiliary chamber estimated at 30 days, half-speed operation of main chamber estimated at 45 days. Only a 1% chance is assigned to this repair level for both chambers. Future reliability is assumed to be improved by setting hazard rate back 10 years. A break down of costs for both chambers is supplied below.

Main chamber, major overhaul to all 4 sets of valve machinery →	$ 600,000
Reduce repair fleet on-site 45 days at $17,500 per day →	<u>$ 787,500</u>
Total for main chamber, major overhaul →	$1,387,500
Aux. chamber, major overhaul to all 2 sets of valve machinery →	$ 300,000
Reduce repair fleet on-site 30 days at $17,500 per day →	<u>$ 525,000</u>
Total for auxiliary chamber, major overhaul →	$ 825,500

Culvert Valve Machinery Major Failure, Replace Major Component. This is considered to be the most likely repair scenario under the major failure branch. A 23.75% chance is assigned to this repair level. The failure assumes a single valve machinery set needs a major component replaced. Closure time for auxiliary chamber is estimated at 10 days, half-speed operation of main chamber assumed to be 10 days as well. Overall repair cost assumed to be $190,000 for either chamber. Cost includes $15,000 for the component and $175,000 for reduced fleet time on-site for 10 days. Future reliability is not improved under this scenario. Same costs are assumed for main and auxiliary chamber since only replacing a component on one set of culvert valve machinery.

Culvert Valve Machinery Minor Failure, Overhaul Machinery. This assumes a failure of the culvert valve machinery, however, the valve machinery can be made serviceable again. Closure time for auxiliary chamber estimated at 15 days, half-speed operation of main chamber estimated at 30 days. A 7.5% chance is assigned to this repair level for both chambers. Future reliability is assumed to be improved by setting hazard rate back 10 years. The difference between the minor failure overhaul and the major failure overhaul is the assumption that only less costly, smaller components would need to be replaced in the minor failure branch. A break down of costs for both chambers is supplied below.

Main chamber, overhaul to all 4 sets of valve machinery →	$350,000
Reduce repair fleet on-site 30 days at $17,500 per day →	$525,000
Total for main chamber, overhaul of valve machinery →	$875,500
Aux. chamber, major overhaul to all 2 sets of valve machinery →	$175,000
Reduce repair fleet on-site 15 days at $17,500 per day →	$262,500
Total for auxiliary chamber, overhaul of machinery →	$437,500

Culvert Valve Machinery Minor Failure, Replace Minor Component. This is considered to be the most likely repair scenario. A 67.5% chance is assigned to this repair level. The failure assumes a single valve machinery set needs a minor component replaced. Closure time for auxiliary chamber is estimated at 5 days, half-speed operation of main chamber assumed to be 5 days as well. Overall repair cost assumed to be $97,500 for either chamber. Cost includes $10,000 for the component and $87,500 for reduced fleet time on-site for 5 days. Future reliability is not improved under this scenario. Same costs are assumed for main and auxiliary chamber since only replacing a component on one set of culvert valve machinery.

Hydraulic System Event Trees

The event trees associated with the hydraulic system must also be broken into two separate event trees since shear amount of piping is greater for the main chamber. It is assumed that any type of failure of the hydraulic piping system causes chamber closure. The main and auxiliary hydraulic system event trees are shown in Figures 6.7.8.C and 6.7.8.D, respectively. The event trees are the same for both chambers with the exception of the costs and closure time associated with having more hydraulic piping for the main chamber.

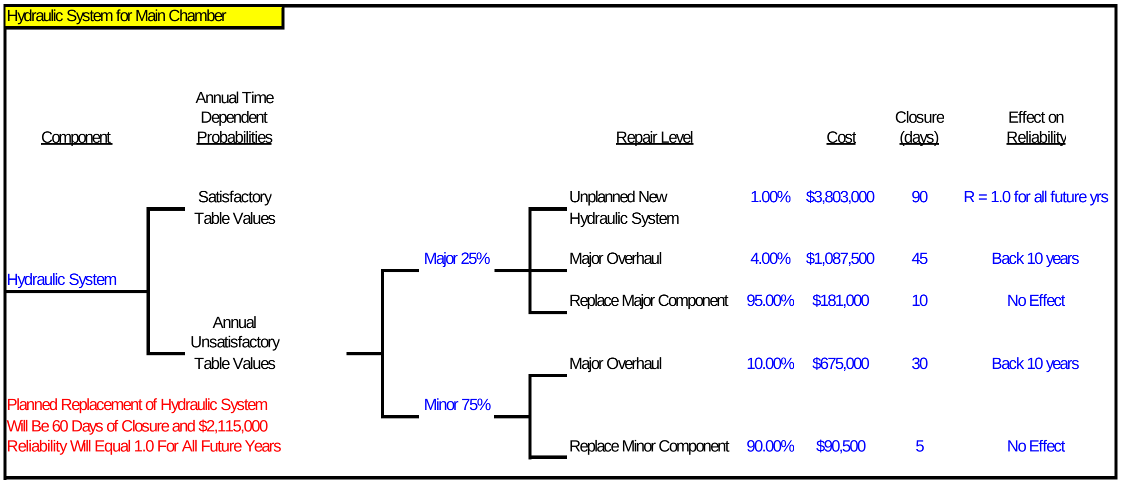


Figure 6.7.8.C. Main Chamber Hydraulic System Event Tree

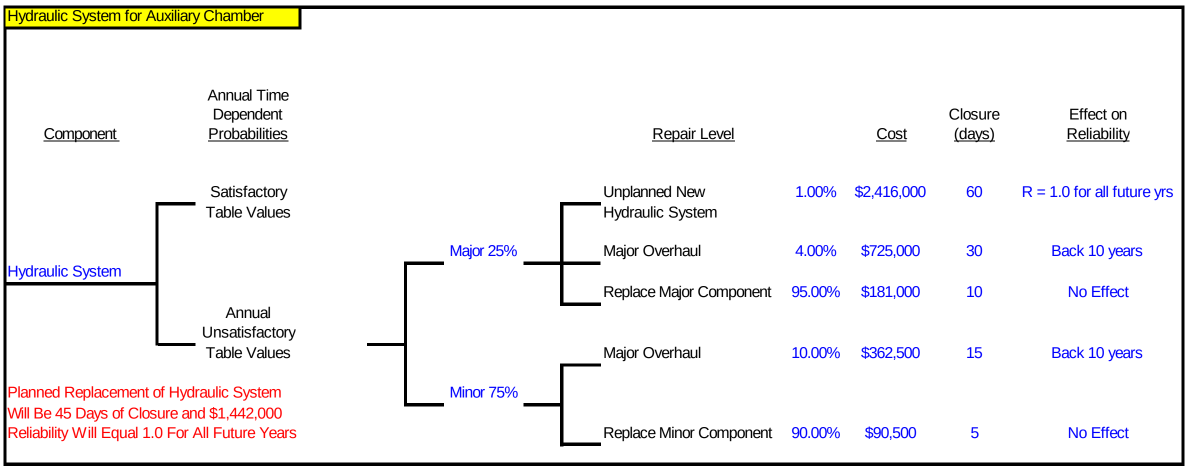


Figure 6.7.8.D. Auxiliary Chamber Hydraulic System Event Tre e

Hydraulic System Major Failure, Unplanned New Hydraulic System. This repair level assumes a catastrophic failure of the hydraulic system where the whole system needs to be replaced. New piping needs to be purchased and installed. Closure time assumes 90 days for the main and 60 days for the auxiliary chamber. A break down of the cost is supplied below.

Main chamber, new hydraulic piping system →	$2,228,000
Reduce fleet on-site 90 days on-site at $17,500 per day →	<u>$1,575,000</u>
Total for main unplanned hydraulic system →	$3,803,000
Aux. chamber, new hydraulic piping system →	$1,366,000
Reduce fleet on-site 60 days on-site at $17,500 per day →	<u>$1,050,000</u>
Total for aux. unplanned hydraulic system → $2,416,000	

This repair level is assumed to be the least likely of all the options. A 0.25% chance of occurrence was assigned to this repair level. The 0.25% is calculated by taking the 25% associated with the major failure branch and multiplying to the 1% assigned to the unplanned hydraulic system repair level. With a new hydraulic system, an updated reliability of 1.0 is assigned for the rest of the study period.

Hydraulic System Major Failure, Major Overhaul. This assumes a major failure of the hydraulic system, however, portions of the hydraulic system are salvaged for future service. Closure time for auxiliary chamber estimated at 30 days, while 45 days of closure is assumed for the main chamber. Only a 1% chance is assigned to this repair level for both chambers. Future reliability is assumed to be improved by setting hazard rate back 10 years. A break down of costs for both chambers is supplied below.

Main chamber, major overhaul to the hydraulic system →	$ 300,000
Reduce repair fleet on-site 45 days at $17,500 per day →	$ 787,500
Total for main chamber, major overhaul →	$1,087,500
Aux. chamber, major overhaul to the hydraulic system →	$ 200,000
Reduce repair fleet on-site 30 days at $17,500 per day →	$ 525,000
Total for auxiliary chamber, major overhaul →	$ 725,500

Hydraulic System Major Failure, Replace Major Component. This is considered to be the most likely repair scenario under the major failure branch. A 23.75% chance is assigned to this repair level. The failure assumes a lengthy section of the hydraulic piping system needs to be replaced. Closure time for both the main and auxiliary chambers is estimated at 10 days. Overall repair cost assumed to be $190,000 for both chambers. Cost includes $6,000 for the piping and $175,000 for reduced fleet time on-site for 10 days. Future reliability is not improved under this scenario.

Hydraulic System Minor Failure, Overhaul Piping System. This assumes a failure of the hydraulic system, however, the majority of the hydraulic system is salvaged for future service. Closure time for auxiliary chamber estimated at 15 days, while 30 days of closure is assumed for the main chamber. A 7.5% chance is assigned to this repair level for both chambers. Future reliability is assumed to be improved by setting hazard rate back 10 years. A break down of costs for both chambers is supplied below.

Main chamber, overhaul to the hydraulic system →	$150,000
Reduce repair fleet on-site 30 days at $17,500 per day →	$525,000
Total for main chamber, overhaul →	$675,000
Aux. chamber, overhaul to the hydraulic system →	$100,000
Reduce repair fleet on-site 15 days at $17,500 per day →	$262,500
Total for auxiliary chamber, major overhaul →	$362,500

Hydraulic System Minor Failure, Replace Minor Component. This is considered to be the most likely repair scenario at 67.5%. The failure assumes a short section of the hydraulic piping system needs to be replaced. Closure time for both the main and auxiliary chambers is estimated at 5 days. Overall repair cost assumed to be $91,500 for both chambers. Cost includes $3,000 for the piping and $87,500 for reduced fleet time on-site for 5 days. Future reliability is not improved under this scenario.

6.7.9 Results and Calibration

One of the first tasks involved with calibrating the mechanical systems model was to review the initial results to determine if the model was producing reasonable results. The initial results indicated that the hazard rates were much higher than what was actually representative for both J.T. Myers and Greenup. Upon further review of the model input, it was decided by the engineering team that the failure rates for many of the components had characteristic lives that were much shorter than what had actually occurred in the field. The team decided that since the failure rate data is based mainly upon military hardware that it doesn't truly represent the rates that we might see under operation of a lock and dam. Therefore, the operational repair records were researched to determine how often there had been major repair/rebuilding of the machinery parts associated with the miter gates and culvert valves. The mechanical system at J.T. Myers was operational in 1972. From the operation's repair records at J.T. Myers, it is known that many of the mechanical parts were rebuilt or replaced on both the culvert valve machinery and miter gate machinery during major dewaterings of the main chamber in 1989 and auxiliary chamber in 1990. It is also known that recent repair work at J.T. Myers included rebuilding the hydraulic cylinders for the gates and valves. The present maintenance policy is to rehabilitate the machinery about every 15 years for both valve and gate machinery. Therefore, the failure rates were altered from the rates provided in the reference manual to match a characteristic life of approximately 15 years. This change brought the hazard rates down to what the team considered accurate within the confines of the model itself. Since miscellaneous hydraulic repairs have occurred over the years of operation, it appears as if repairs are only initiated as needed. Therefore, the failure rates for the hydraulic system were left unchanged from those in the reference manual. These results are presented in the next section.

J.T. Myers Lock Mechanical System Hazard Rates

The hazard rates for the mechanical components for J.T. Myers Lock are shown in graphical form in Figures 6.7.9.A, 6.7.9.B, and 6.7.9.C. Figure 6.7.9.A depicts the miter gate machinery for both the main and auxiliary chamber at J.T. Myers. Figure 6.7.9.B shows the culvert valve machinery for both chambers. Both sets of hazard rates are very low due to the fact that the machinery associated with both of these components is typically rehabilitated every 15 to 20 years. Figure 6.7.9.C depicts the hazard rate associated with the hydraulic system for the main and auxiliary chambers at J.T. Myers. As evidenced by the graph, the hazard rates are significant throughout the study period. This can be attributed to the fact that there has been no wholesale replacement of the hydraulic piping system. Repairs to the hydraulic system are typically done on an as needed basis and are not scheduled for rehabilitation/replacement as part of normal maintenance. As expected, the hazard rates for the main chamber are higher than for the auxiliary chamber for like components as the rate is a function of the number of operating cycles for each component.

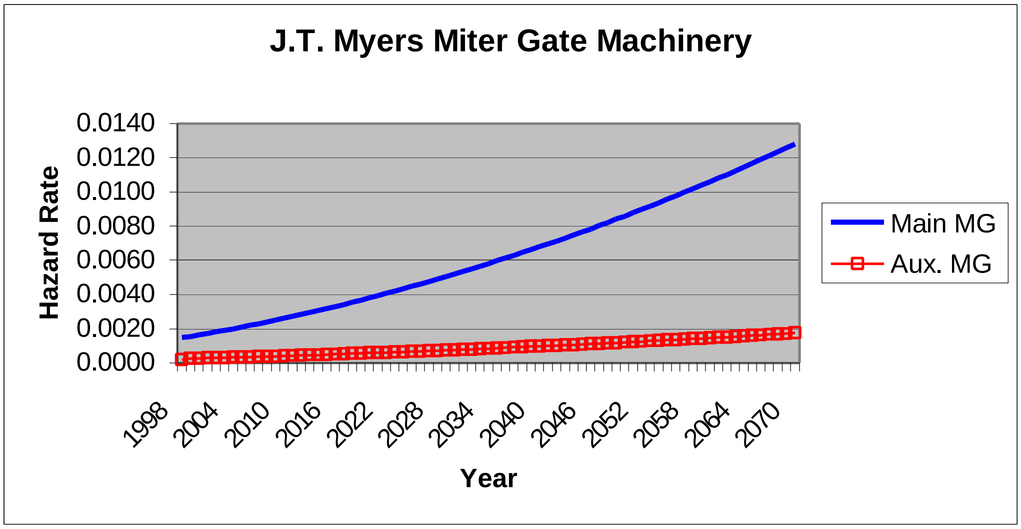


Figure 6.7.9.A J.T. Myers Miter Gate Machinery Hazard Rates

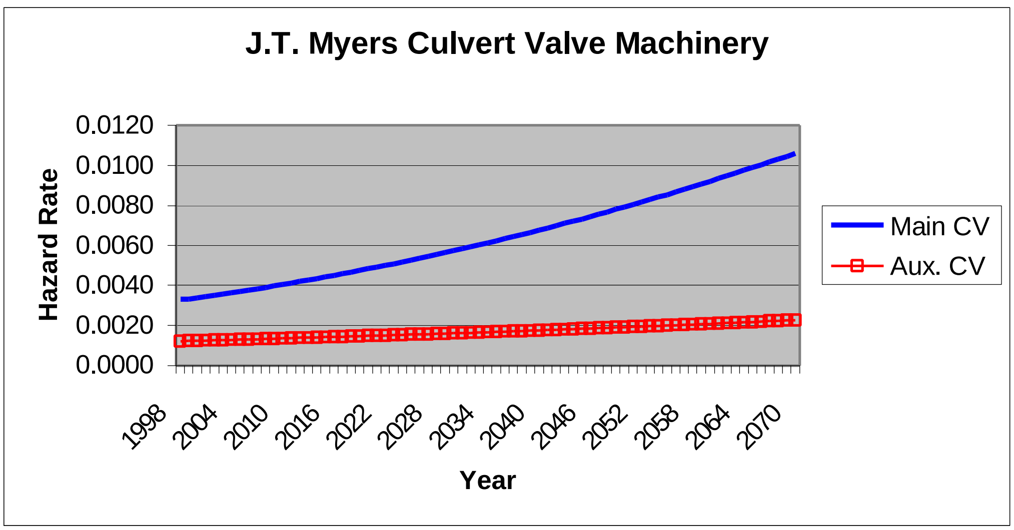


Figure 6.7.9.B. J.T. Myers Culvert Valve Machinery Hazard Rates

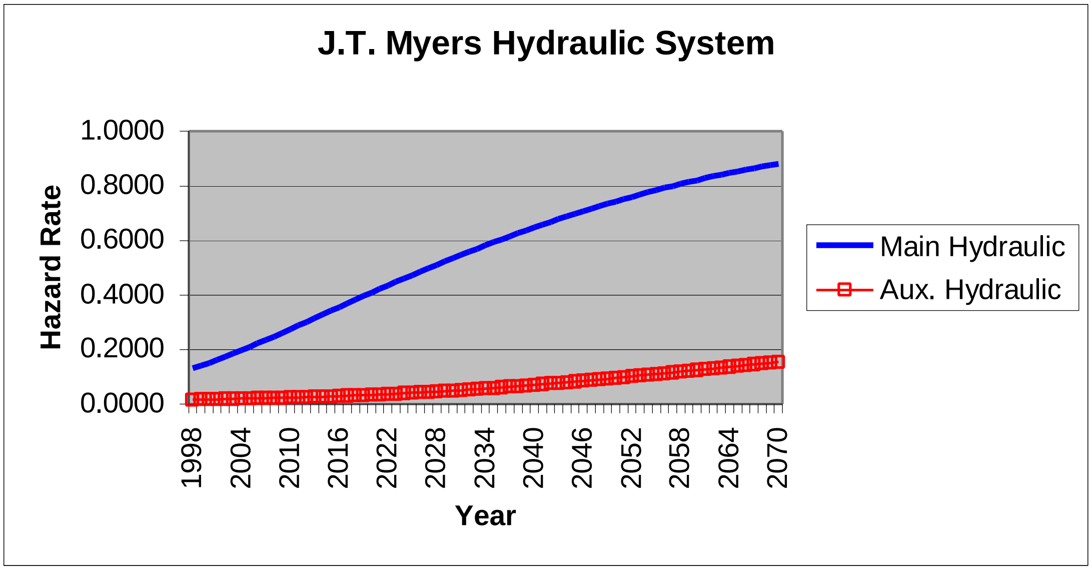


Figure 6.7.9.C. J.T. Myers Hydraulic System Hazard Rates

Greenup Lock Mechanical System Hazard Rates

The hazard rates for the mechanical components for Greenup are shown in graphical form in Figures 6.7.9.D, 6.7.9.E, and 6.7.9.F. Figure 6.7.9.D depicts the miter gate machinery for both the main and auxiliary chamber at Greenup. Figure 6.7.9.E shows the culvert valve machinery for both chambers. Figure 6.7.9.F depicts the hazard rate associated with the hydraulic system for the main and auxiliary chambers at Greenup. Reviewing the hazard rates for Greenup indicate similar results as those for like components at J.T. Myers. The only significant hazard rates for each project are encountered for the hydraulic system of both the main and auxiliary chambers. The other components, machinery for the culvert valves and miter gates, are rehabilitated every 15 to 20 years on average, and the failure rates in the model were adjusted to reflect that maintenance. The hazard rate for each component is tied to the reliability block diagram for each site as well as the operating cycles. Since the same miter gate machinery reliability computation is used for both sites, the Greenup miter gate machinery hazard rate is slightly lower than J.T. Myers since the number of "average" projected cycles over the study period is lower for Greenup. However, both miter gate machinery hazard rates remain insignificant. The same can be said for the culvert valve machinery hazard rates when comparing Greenup with J.T. Myers.

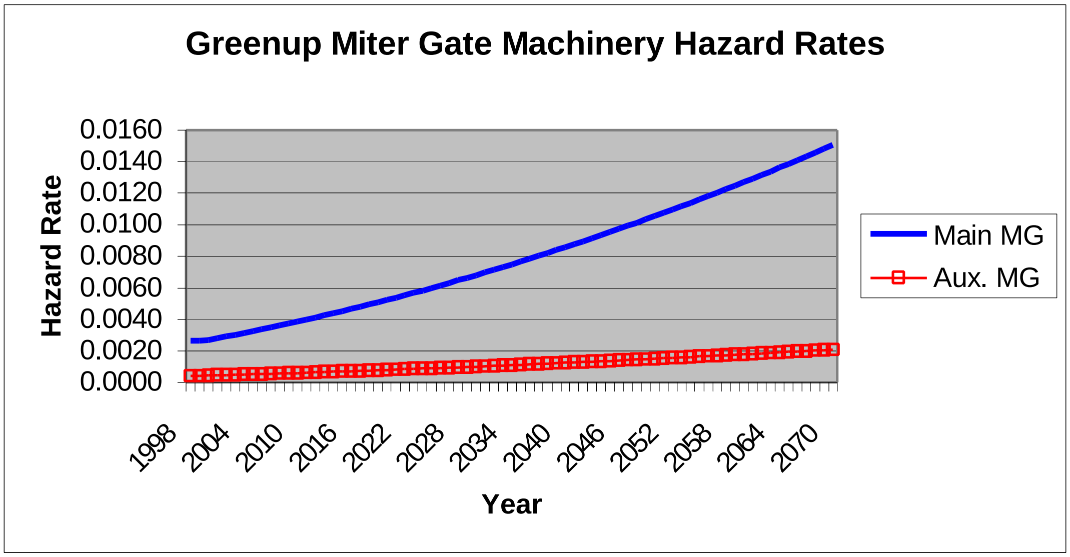


Figure 6.7.9.D. Greenup Miter Gate Machinery Hazard Rates

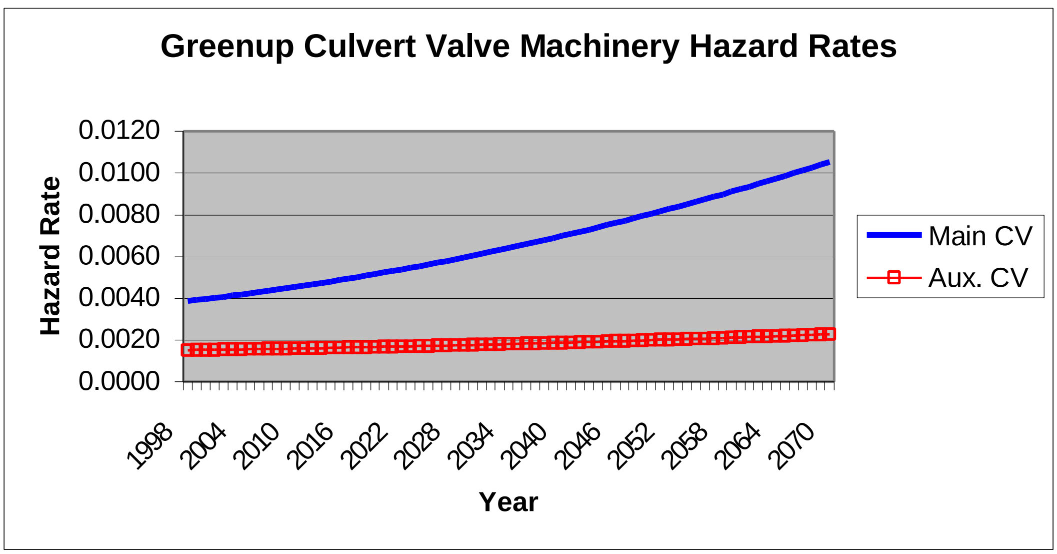


Figure 6.7.9.E. Greenup Culvert Valve Machinery Hazard Rates

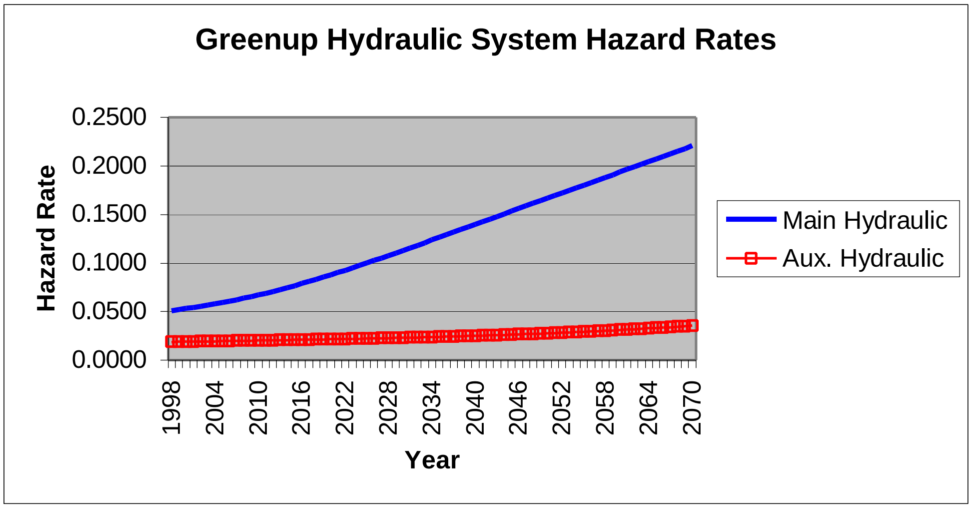


Figure 6.7.9.F. Greenup Hydraulic System Hazard Rates

6.7.10 Economic Results for Mechanical System at J.T. Myers and Greenup

The hazard rates shown above along with the component and chamber specific event trees were handed to the economists to determine the if replacing the components were justified as opposed to a fix-as-fails approach. The results for all the mechanical components at both J.T. Myers and Greenup are shown in Table 6.7.10.A. The results indicate that fix-as-fails is the most economic alternative for the majority of all components. Only the hydraulic system at J.T. Myers is justified for a replacement. This is mainly due to the high hazard rates associated with this component at J.T. Myers. Even though an optimum time was not set within the study period, it is a better alternative to replace the component once it becomes cheaper than the fix-as-fails option. Therefore, it was decided to set the timed replacement for the J.T. Myers main chamber hydraulic system for 2020, while the auxiliary hydraulic system was set for 2030.

The results from Table 6.7.10.A are used in the overall economic analysis to provide both the reliability-based costs and closures that are to be fed into the model for the mechanical components at J.T. Myers and Greenup. The reliability-based information plays a key part in the economists determining net benefits of newer, higher capacity projects versus existing projects at each of these sites. Having a lengthy reliability-based major component replacement closure of the main chamber is much more costly when a project only has a 600-foot auxiliary lock to service navigation traffic as compared to a project that has twin 1200-foot lock chambers.

Using the event trees for both the main and auxiliary chamber hydraulic systems, projected replacement closures are input into the ORMSS cost and closure matrices for J.T. Myers. As shown in the event trees, a 60-day closure with a replacement cost of $2,115,000 is input into the matrix for the J.T. Myers main chamber in 2020 (the justified replacement timing for this component). A 45-day closure at a replacement cost of $1,142,000 is input into the J.T. Myers matrix for the auxiliary chamber hydraulic system in 2030. For the other mechanical components that are not independently justified for replacement, reliability-based closure costs associated with the hazard rate are added to the cost/closure matrices for each chamber.

Table 6.7.10.A. Economic Results of J.T. Myers/Greenup Mechanical Reliability

Average Annual Costs of J.T. Myers and Greenup Mechanical Components							
Description of Option	Chamber	J.T. Myers Gate Machinery	Greenup Gate Machinery	J.T. Myers Valve Machinery	Greenup Valve Machinery	J.T. Myers Hydraulic	Greenup Hydraulic
Fix-as-Fails	Main	**$45,200**	**$26,600**	**$64,700**	**$35,700**	$4,169,500	**$625,800**
Replace in 2010	Main	$1,545,900	$1,073,100	$196,700	$197,600	$4,546,100	$4,250,700
Replace in 2020	Main	$1,150,100	$805,700	$120,500	$113,400	**$3,640,500**	$3,146,500
Replace in 2030	Main	$823,900	$580,800	$79,700	$71,500	$2,778,800	$2,246,800
Replace in 2040	Main	$813,800	$500,400	$66,800	$52,500	$2,340,700	$1,822,700
Fix-as-Fails	Auxiliary	**$1,500**	**$1,700**	**$2,400**	**$3,000**	$95,200	**$38,300**
Replace in 2010	Auxiliary	$215,600	$206,700	$124,500	$115,700	$159,700	$139,600
Replace in 2020	Auxiliary	$122,400	$107,200	$75,700	$61,000	$102,600	$91,600
Replace in 2030	Auxiliary	$63,400	$58,500	$39,800	$35,400	**$70,400**	$70,300
Replace in 2040	Auxiliary	$38,900	$43,900	$27,200	$32,700	$65,900	$84,900

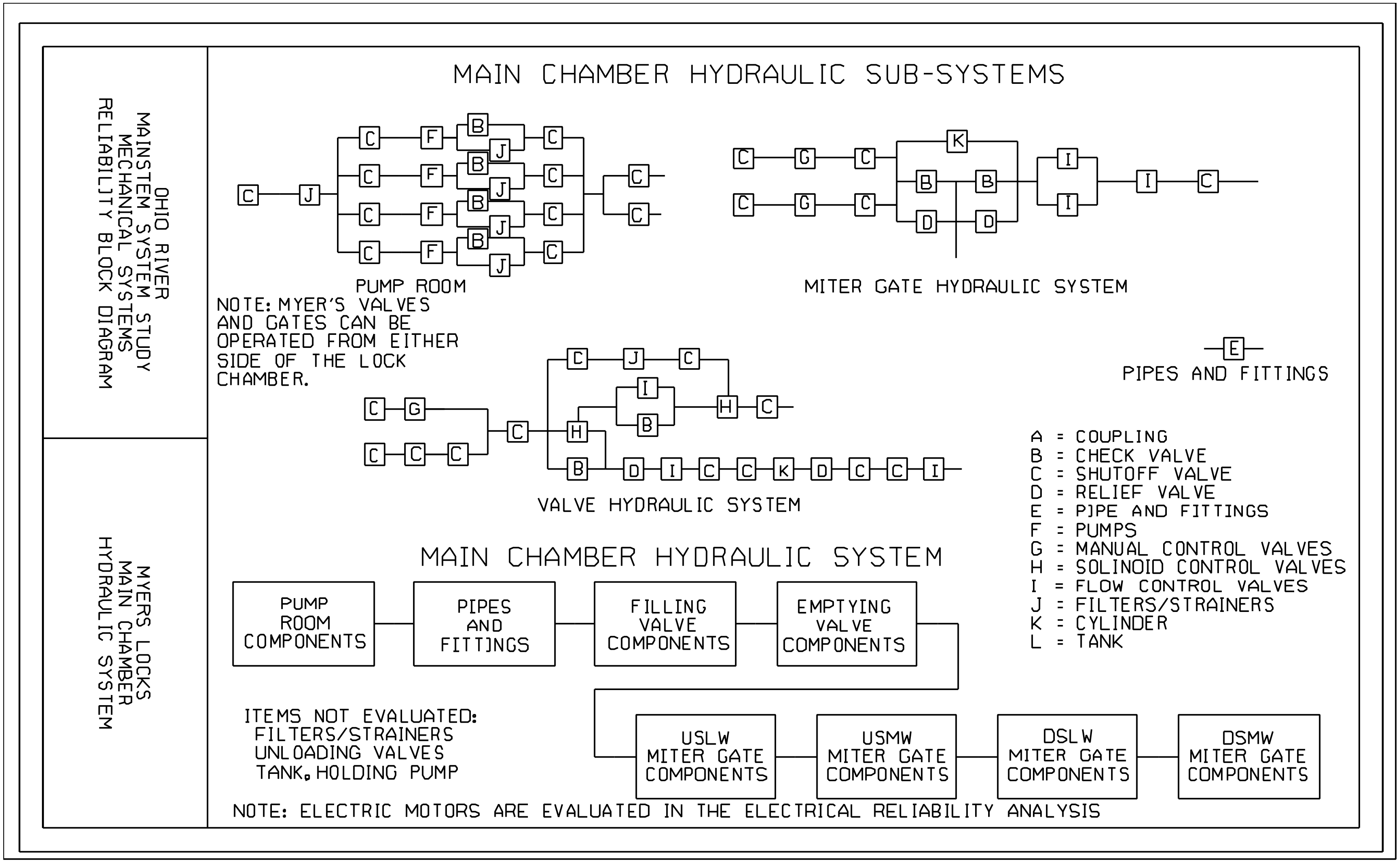


Figure 6.7.4.D J.T. Myers Hydraulic System Line Diagram and RBD

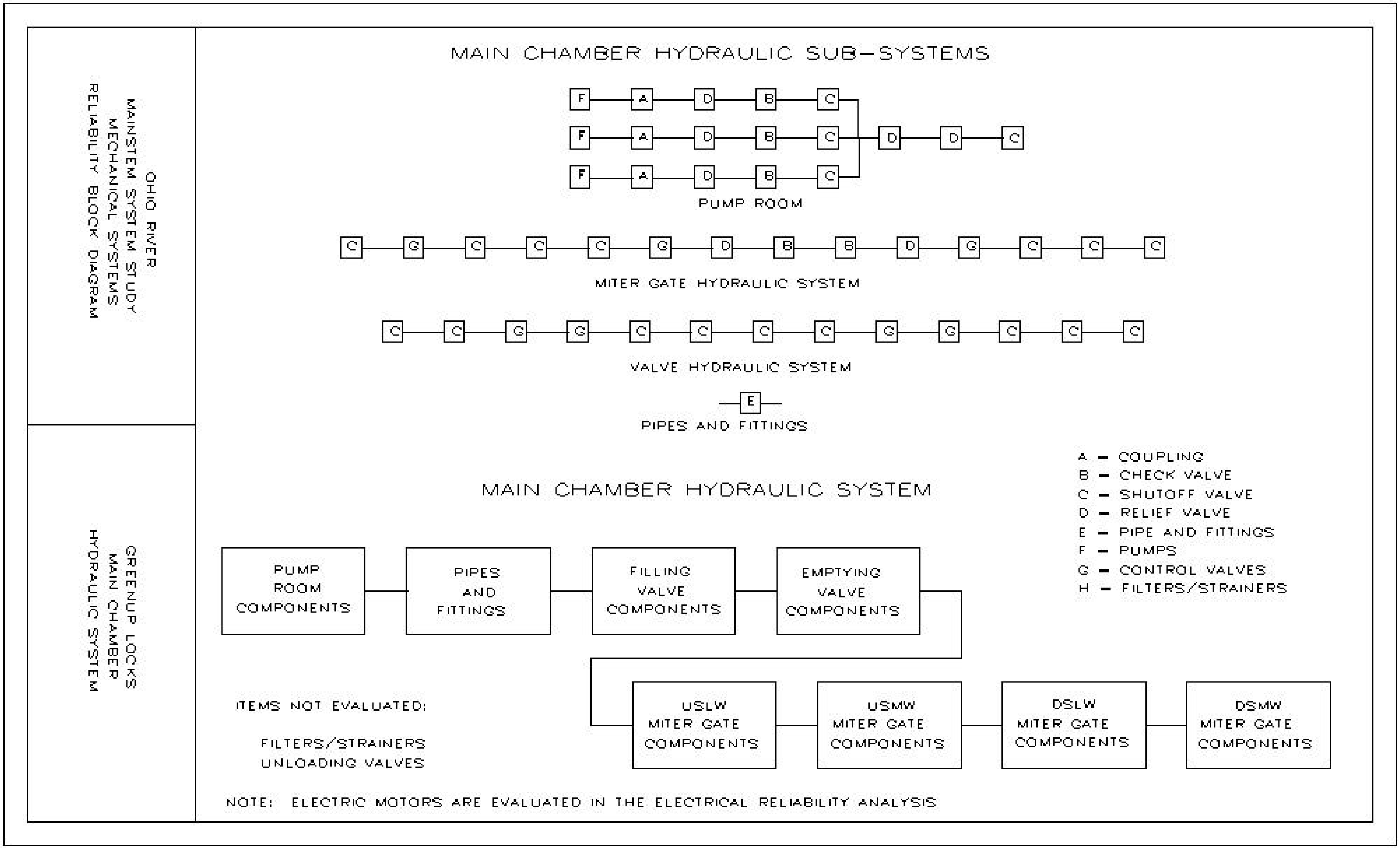


Figure 6.7.4.E. Greenup Main Chamber Hydraulic System Line Diagram and RBD

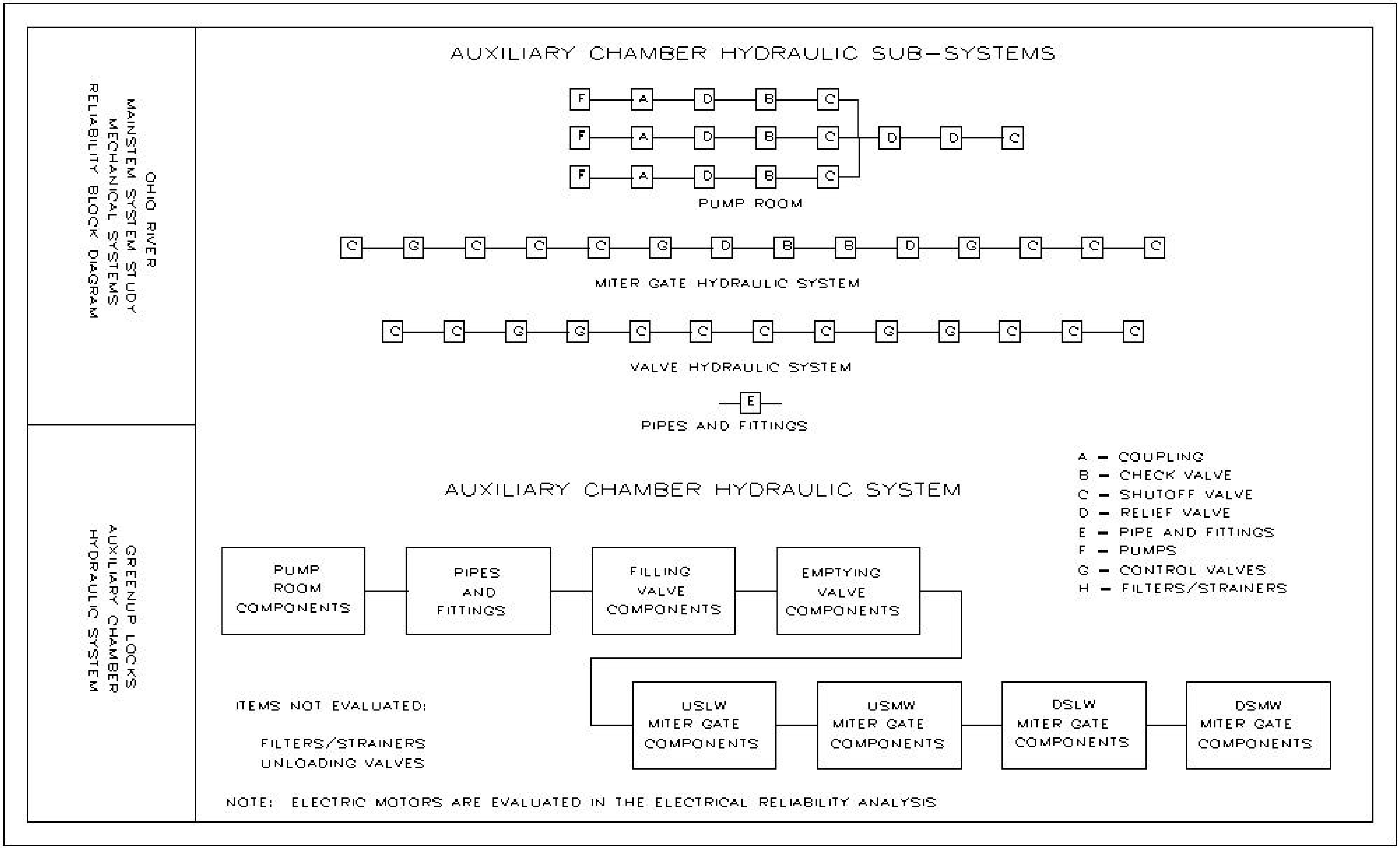


Figure 6.7.4.F Greenup Auxiliary Chamber Hydraulic System Line Diagram and RBD

6.8 LOCK WALL MONOLITH RELIABILITY

There are two basic types of lock walls on the Ohio River system, unanchored concrete gravity monoliths and anchored concrete monoliths. The unanchored concrete monolith lock walls are not considered to be time dependent from a reliability standpoint. The anchored concrete monolith lock walls are considered to be time dependent (reliability changes with time) because the anchors are subjected to fatigue and corrosion. There are only three sites on the Ohio River that have anchored concrete monoliths for lock walls. These are Emsworth, Dashields, and Montgomery (EDM) Locks and Dams in the Pittsburgh District. All other remaining sites, including Greenup and J.T. Myers, have unanchored concrete gravity monoliths for lock walls. As stated previously, their reliability is not assumed to change with time. At the time of this interim report, the results for the unanchored concrete gravity monolith lock wall reliability have been completed at the following sites: Hannibal, Belleville, R.C. Byrd, Greenup, Markland, McAlpine main chamber, Cannelton, Newburgh, J.T. Myers, and Smithland Locks and Dams. The sites with unanchored concrete gravity monoliths that need to be completed are New Cumberland, Pike Island, Willow Island, Racine, and Meldahl. These remaining sites will be completed as part of the final ORMSS report, as well as the anchored lock walls at EDM.

Within the unanchored concrete gravity lock wall category, there are three types of monoliths that have been analyzed for reliability. These are a “typical” land wall, middle wall, and river wall within the limits of each lock chamber. Additionally, the lower, middle wall auxiliary chamber miter gate monolith was analyzed. The engineering team chose this miter gate monolith at each site since it generally experiences the highest uplift, particularly in the maintenance case. Since the uplift has proven to be the most critical load on concrete gravity structures, the team chose to look at this particular monolith.

All of the unanchored lock wall sections analyzed are concrete gravity structures founded on rock. Additionally, all of the unanchored monoliths analyzed are concrete structures founded on rock and are not stabilized with active or passive rock anchors. There are three walls made of individual concrete, gravity monoliths that form the lock chamber. The land wall and one side of the middle wall form the auxiliary chamber. The river wall and other side of the middle wall form the main chamber. Since the time or funding was not sufficient to investigate every possible monolith cross-section for reliability analyses, a typical monolith was selected to be representative for each wall.

6.8.1 Load Cases for Lock Wall Reliability

Because the structures are massive concrete structures without anchors, they are not subject to fatigue and corrosion associated with steel structures. As a result, no deterioration over the operational life of the structure is considered and the reliability of the structures is assumed to be independent of time. Therefore, the reliability is assumed to be constant over the study period. This is consistent with HQUSACE reliability guidance for unanchored concrete gravity monolith structures. Since the reliability of the structure is based on limit states and not design values, unsatisfactory performance modes considered for the gravity monoliths are overturning, sliding, and bearing of the rock foundation **without any safety factors applied to the analysis**. The limit states established for the unsatisfactory performance modes are as follows: overturning – a negative effective base in compression, sliding – the driving horizontal forces exceed the resisting horizontal forces, and bearing – the resultant monolith toe bearing pressure exceeds the maximum peak bearing strength of the foundation rock or subjacent rock.

In general, calculations were based on current Corps of Engineers lock design criteria. Two loading conditions are considered for the unanchored lock wall monoliths: the normal operating condition and the maintenance condition. The normal operating condition represents the usual daily cyclic loads experienced by the lock monoliths. Dewatering the chamber is the maintenance condition. Table 6.8.1.A depicts the loading conditions for both situations for all three monoliths. As an example, the values and descriptions in the table are representative of the conditions at Markland. Normal upper pool at Markland is elevation 455.0. This generally does not vary significantly and therefore is assumed to be constant in the model. Normal lower pool elevation is 420.0; however, the lower pool fluctuates and is a random variable in the reliability analysis. The major external loadings experienced by a land wall are lateral earth pressure, hydrostatic pressure due to the saturation level of the backfill, uplift, hawser pull, and the fluctuating pool elevation in the lock chamber. The middle and river walls are subjected primarily to uplift, hawser pull, and fluctuating pool elevations in the chambers or river. The miter gate monolith is also subjected to hydrostatic effects, but also the miter gate loads. Barge impact is excluded from the analysis since the lock chamber monoliths are not part of the navigational approach system.

Table 6.8.1.A. Load Cases for Lock Wall Monoliths

Monolith	Load Case	
	Normal Operating Condition	Maintenance Condition
Land	Backfill saturated to EL. 455.0 and fluctuating lower pool in main chamber.	Backfill saturated to EL. 455.0 and the main chamber dewatered, EL. 398.0.
Middle	Main chamber at upper pool, EL. 455.0 and auxiliary chamber at fluctuating lower pool.	Main chamber at upper pool, EL. 455.0 and auxiliary chamber dewatered, EL. 398.0.
River	Auxiliary chamber at upper pool, EL. 455.0 and the river at fluctuating lower pool.	River at fluctuating lower pool (<EL 431.08) and auxiliary chamber dewatered, EL 398.0.

For the analysis of all gravity structures, an external force resisting overturning was added to the model to account for rock embedment where appropriate. If the embedment was minimal, this external force was neglected in the analysis. The model calculates this force as the passive crossbed shear resistance of the rock wedge on the down stream face of the monolith. For the miter gate monoliths, the analysis included no resistance from the adjacent miter gate sill or adjacent monoliths.

6.8.2 Loading Assumptions

The gravity loads considered in the analysis are due to the weights of the water and soil above the monolith, water within the culvert, and the concrete monolith. For an example of model input, the soil/rock random variables and constant values for the Markland project are provided in the Tables 6.8.2.A and 6.8.2.B, respectively. For the case where the moist soil unit weight exceeds the saturated soil unit weight, the moist soil unit weight is made equal to the saturated soil unit weight in the stability analysis. Lateral earth pressure of the backfill is computed using the full at-rest pressure coefficient (K_o) that is calculated from Jacky's Equation, since the lock monoliths are founded on rock[1,2]. For Markland, the saturation level in the backfill is assumed to be constant and equal to the normal upper pool elevation EL 455.0. Uplift is assumed to be acting on the entire base of the monolith. The uplift pressure values are based on the varying lower pool elevation, constant upper pool elevation, and/or the saturation level in the backfill. The distribution of the uplift pressure was calculated using a derived closed-form solution for uplift that is a function of the overturning and resisting moments, uplift pressures at the toe and heel of the structure, and the resultant vertical load. It is assumed that a uniform uplift pressure equivalent to the maximum hydrostatic pressure at the heel of the base acts on the portion of the base not in compression. A hawser pull is applied to a structure under the normal operating condition for 20 percent of the Monte Carlo trials [typically 10,000 trials] [3]. The hawser pull-force value normal to the face of a monolith is established from the guidance in ETL 1110-2-321 and the point of application is assumed to be 5 ft above the pool elevation[4,5]. Vertical shear (downdrag), acting along the wall-soil interface due to differential settlement of the backfill, is available in the model but was not utilized in the stability analyses since the lock monoliths are completely stable for both normal operating and maintenance conditions.[2,5]

For the miter gate monolith analysis, full hydrostatic head was applied to the upstream and downstream faces and uplift on the base of the structure varies linearly from 100% of headwater to 100% of tailwater with no effect from foundation drains. In the case of the base not being entirely in compression, it was assumed a tension crack is formed and 100% of headwater pressure was applied along the length of the crack then the uplift varies linearly to tailwater from that point. For the normal condition, the hydrostatic and uplift pressures upstream of the centerline of the pintle were based on the upper pool level in the auxiliary chamber, and those downstream were based on lower pool level. All sites with unanchored concrete gravity monoliths have miter gates that are horizontally framed. Therefore, the miter gates transfer the load produced by the differential head directly to the monolith in the normal condition. During the maintenance condition, the weight of the hanging gate is transferred to the monolith as a force couple at the top anchorage and the pintle.

The tables and description of the conditions at Markland are only shown to give the reader a flavor of the model and how it works. Each project that has had the analysis completed had the same load cases as shown in this narrative. Additionally, the random variables and constants are site-specific values but are input into the model the same as shown for Markland.

6.8.3 Random Variables and Constants in the Analysis

The geotechnical shear strength parameters for all sites are based on information obtained from the as-built drawings, design memoranda, foundation reports, periodic inspection reports, and reference material. Each district's geotechnical engineers provided the necessary data to complete the analysis. Cross-sections, boring logs, N-values, and laboratory test results are used to determine the range in strength values. Very limited test results are available for the majority of the sites. As a result, typical strength values are obtained from reference material and original design values. The probabilistic values used in the reliability analyses include the type of probability distribution function, mean, standard deviation, range, coefficient of variance, and correlation coefficient, and are provided in the following table. Unit weights, shear strength parameters, and ultimate bearing capacity values are provided for the soil and rock foundation. Cross-bed shear strengths are also provided for the monoliths embedded in rock.

Table 6.8.2.A Random Variables for Markland Lock Wall Stability Model

Variable	Mean	Standard Deviation	Maximum	Minimum	Distribution	Units	Description
Soil:							
Mst Unit Wt	0.115	0.003	0.124	0.106	Normal	kcf	Driving soil, unit weight, moist
Sat. Unit Wt	0.125	0.004	0.137	0.113	Normal	kcf	Driving soil, unit weight, saturated
Phi, internal	33	2	38	30	Normal	deg	Driving soil, internal friction angle
Rock:							
Phi, sliding	38	4	45	35	Normal	deg	Rock, sliding friction angle
c, sliding	20	20	25	0	Normal	psi	Rock, sliding shear strength
Phi crossbed	47	4.5	57	37	Normal	deg	Rock, cross-bed friction angle
c, crossbed	75	25	100	50	Normal	psi	Rock, cross-bed shear strength
Sat Unit Wt	0.1672	0.002	0.1697	0.1660	Normal	kcf	Rock, saturated unit weight
BrgCapacity	2083.3	208.3	2430.6	1736.1	Normal	psi	Rock, ultimate bearing capacity
Lower Pool					CDF [1/,2/]	NA	Lower Pool elevation
Hawser Pull	57.5	11.5	80.5	34.5	Normal	kip	Hawser pull force, normal to face

[1/] Cumulative Density Function established for Lower Pool is used.
[2/] For river wall R-48, the maintenance condition, the maximum main chamber is flooded when the lower pool elevation exceeds EL 431.08.
NA - Not applicable.

Table 6.8.2.B. Constants for Markland Lock Wall Stability Model

Constant	Value	Units	Description
Conc Unit Wt	0.1475	Kcf	Concrete, unit weight
Water Unit Wt	0.0625	Kcf	Water, unit weight
Saturation Level	455.0	Ft	Water saturation level in backfill
Upper Pool	[1/] 455.0	Ft	Upper Pool elevation

[1/] When L.P. EL > U.P. EL – 1 ft, U.P. EL = L.P.EL + 1 ft.

6.8.4 Lock Wall Reliability Model Computations

The Microsoft Excel™ spreadsheet and the @Risk™ add-on application is comprised of six sheets (*Input Parameters*, *Monolith Geometry*, *Soil Geometry*, *Water Elevation*, *Stability Analysis*, and *Stability Results*) and two visual basic modules (*Update* and *VBProgram*). @Risk™ is an add-on software application for Microsoft Excel™ that provides Monte Carlo simulation for reliability analysis. The material properties and input data are represented by probability distribution functions instead of discrete values. For each Monte Carlo trial, material properties and input data are randomly selected according to their respective probability distributions for the stability analysis. The structure is analyzed for its stability in overturning, sliding, and bearing. Any unsatisfactory performance is tabulated for each trial. A sufficient number of trials, 10,000 for this model, are required to achieve convergence and a particular level of confidence in the simulation results. The general model spread sheets are set up similar to the model for the miter gate sills. Refer to Section 6.10 to view the miter gate sill model spread sheets.

For the lock wall monolith reliability model, the probability distribution functions, parameters, and constants are provided in the *Input Parameters* sheet. The geometry, voids, and centroid computation of the monolith are provided in the *Monolith Geometry* sheet. Soil geometry is provided for one or two types of backfill and the sheet calculates the moist and saturated soil layers, weights, and centroids using the visual basic *Update* functions. The lower pool cumulative density function and upper pool discrete value are provided in the *Water Elevation* sheet. Soil and rock elevations for computation of driving and resisting forces are provided in the *Stability Analysis* sheet. The stability calculations and results for overturning, sliding, and bearing are provided in the *Stability Results* sheet. A visual basic module is used to track unsatisfactory performances during the Monte Carlo trials. The respective unsatisfactory performances for each limit state and cumulative unsatisfactory performances are also tabulated on this sheet.

The stability analyses follow the guidance provided in Chapter 4 of EM 1110-2-2502. For the overturning stability analysis, the vertical and horizontal forces and the resultant moments are summed. The resultant moments are categorized as resisting or overturning moments. The effective base in compression and the uplift is solved for simultaneously using a closed-form solution. The closed-form solution is a function of the overturning and resisting moments, uplift pressures at the toe and heel of the structure, and the resultant vertical load. A negative effective base in compression indicates that the structure performs unsatisfactorily in overturning. Once the effective base and uplift are established, the sliding stability analysis is conducted. The passive resistance of the rock and structural wedge is computed and the resisting forces are summed with the resultant net negative driving forces. If the sum of the resisting and driving forces is negative, the structure performs unsatisfactorily in sliding. The maximum bearing pressure is then calculated and compared to the ultimate bearing capacity for the rock foundation. If the bearing pressure exceeds ultimate bearing strength, the structure performs unsatisfactorily in bearing. Each mode of unsatisfactory performance is tabulated for each trial. However, any trial that results in a calculated unsatisfactory performance in any one or combination of the three performance modes will be counted for reliability purposes as one unsatisfactory performance for the structure.

6.8.5 Results and Conclusions

As stated earlier in this narrative, only reliability runs at Hannibal, Belleville, R.C. Byrd, Greenup, Markland, McAlpine main chamber, Cannelton, Newburgh, J.T. Myers, and Smithland have been completed to date. The runs and possible subsequent economic analysis for the reliability analysis of the unanchored lock wall monoliths at New Cumberland, Pike Island, Willow Island, Racine, and Meldahl still need to be completed. Additionally, the anchored lock wall monolith reliability analysis still needs to be completed at EDM. These will be completed as part of the final ORMSS effort.

For the sites that have been completed, including Greenup and J.T. Myers, no unsatisfactory performances were calculated in 10,000 iterations for both the normal and maintenance load cases. There were no unsatisfactory performance occurrences because of the original safety criteria used in design of the structures. Additionally, each site is founded on sound rock that resists all three possible failure modes.

These results are reasonable and expected since no significant movement of the walls has been noted at any of the sites since construction. Since there were no unsatisfactory performances, the economists did not need to run their analysis for the lock wall monoliths at the sites that have been completed. Thus, the event tree for lock walls is not included with this appendix.

7. References

1. Headquarters, Department of the Army. (1989). "Retaining and Flood Walls," Engineering and Design, EM 1110-2-2502, Washington, DC.
2. Headquarters, Department of the Army. (1997). "Stability Analysis of Concrete Structures," Engineering and Design, EC 1110-2-291, Washington, DC.
3. ORMSS Meetings – Discussions with Operations and Design Sections.
4. Headquarters, Department of the Army. (1993). "Reliability Assessment of Navigational Structures, Stability of Existing Gravity Structures," Engineering and Design, ETL 1110-2-321, Washington, DC.
5. Ebeling, R. M., M. E. Pace, WES, and E. E. Morrison, Jr., N.A.S. Fallon. (1997). "Evaluating the Stability of Existing Massive Concrete Gravity Structures Founded on Rock," Technical Report REMR-CS-54, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

6.9 GUARD AND GUIDE WALL RELIABILITY

Each project on the Ohio River has both guard and guide walls. Guard walls are on the riverside of the riverward lock chamber, which is usually the main chamber for Ohio River locks. Guide walls are on the landside of the landward chamber. The purpose of both the guard and guide wall is to assist navigation traffic in entering and exiting the lock chamber. The guard wall also protects navigation traffic from the dam. There are two guard walls, an upstream and downstream, for each project. Their locations are just upstream and downstream of the main lock chamber. Upstream guard walls were chosen for analysis rather than downstream guard walls or guide walls. Since the model evaluates the stability of the structure under normal operating conditions, the upstream guard wall is most susceptible to large loadings from barge impacts that could cause instability. Additionally, upper guard walls are generally subjected to higher impact forces from barges since the upstream current flowing toward the dam causes an outdraft which pulls the barges into the upstream walls. This is not as prevalent on the downstream end. Also, the high pool differential between the upper and lower pools, barges means impacts from barges to the upper walls occur at a much higher elevation than the lower pool, thus, causing a much greater overturning moment due to impact when compared to the lower guard wall. A photograph looking along the upstream guard wall at a typical Ohio River project is shown in Figure 6.9.A.

Figure 6.9.A. Upstream Guard Wall at Typical Ohio River Project.

6.9.1 Types of Guard Walls

There are three general types of structures that comprise the majority of the guard walls on the Ohio River projects. The first type of wall is a "small" concrete monolith supported on concrete filled cells founded on rock. The second type is a "small" concrete monolith supported on steel bearing piles within soil filled cells. The third is a "typical" concrete gravity monolith with a rectangular base.

The most abundant wall type is the concrete filled cell supported structure founded on rock. This type of structure accounts for approximately half of the Ohio River guard walls. Sites with this type of guard wall include Willow Island, Belleville, Racine, Greenup, Markland, McAlpine, Cannelton, and J.T. Myers. In general, these type walls are found on the lower reaches of the river where tow and lock sizes are generally larger. These structures are not found in the Pittsburgh District.

The second guard wall type is the soil filled cell and steel-bearing pile supported concrete structure. Both the soil filled cell and steel bearing piles are founded on rock. This type of structure is found at New Cumberland, Pike Island, Hannibal, Meldahl, and Newburgh.

The third wall type is a "typical", rectangular base, concrete gravity monolith structure founded on rock. Within this group there are various configurations. The most conventional design is R.C. Byrd. The guard wall acts more like a guide wall because it has soil backfill. This is due to the configuration of the new lock constructed in 1993 through a cut channel. Smithland and Dashields have guard walls that are supported on two narrow rectangular supports that form the walls of the ports. Emsworth has a full rectangular base with the ports formed in the side of the wall, however the base is very narrow.

Montgomery is the only project on the Ohio River where the upper guard wall is unique. The guard wall at Montgomery is a rectangular concrete wall supported on wooden piles. The piles are founded on rock.

At the time of this interim report, the results of the guard wall analysis at Smithland, Dashields, Emsworth, and Montgomery have not been completed. These sites will be completed as part of the ORMSS final report. All the sites where the guard wall reliability analysis has been completed will be forwarded into the final ORMSS report as well.

6.9.2 Guard Wall Reliability Model Description

The proper method of analysis to determine the reliability of each type of guard wall was investigated extensively. Each wall type was investigated independently because of the differences associated with the base of the structures.

The concrete filled cell founded guard wall was analyzed as a gravity structure. The monoliths span between cells effectively tying them together; for one cell or monolith to fail, movement would be required in the adjacent monoliths. Therefore, the "monolith" considered for the model was one monolith and the two cells it spans between, including ½ the weight of the two adjacent monoliths. For stability calculations, the cells are analyzed using the equivalent rectangular base per EM 1110-2-2503. A plan and section of a typical upper guard wall monolith of this type is shown in Figure 6.9.2.A (Markland).

Because the steel sheet pile cell is always submerged there is minimal corrosion to the shell of the base of the structure. Therefore, since the structure is essentially all concrete, there is effectively no deterioration over the design life of the structure and for simplicity, the model is assumed to be independent of time. The reliability model is not considered to be time dependent such that the reliability degrades with time. A single probability of unsatisfactory performance is calculated for the model and used for every year in the economic analysis. This is consistent with HQUSACE guidance for reliability analysis of other ORMSS gravity structure stability models. Due to the massiveness of this type of structure, there are a few possible unsatisfactory performance modes. The unsatisfactory performance modes analyzed in the model are typical overturning, sliding and bearing on the foundation. Because this is a reliability analysis and not a design analysis, an unsatisfactory performance is any load combination resulting in a factor of safety of 1.0 or less for any one or more of the possible modes.

The second type of wall, soil filled cell with steel bearing piles, has little applicable guidance for analyzing this type of structure. Original design calculations were consulted but did not provide much help either as they only considered the piles to support the vertical load of the wall and did not address lateral stability. It is understood that soil filled cells are generally flexible, however, the presence of the steel bearing piles and the concrete cap eliminate nearly all of the theoretical failure modes suggested for soil filled cofferdam cells. Attempts were made to include the bearing piles in the analyses, but many failures were calculated while none are known to have actually occurred. It was decided that the true behavior of the structure was somewhere between a pile founded and a rigid concrete structure, and that this behavior would not be truly captured without performing complicated three dimensional finite element analyses of every structure of this type. This type of analysis is beyond the scope of the study for a structure known not to have significant problems during historical operation. It was determined that treating them as rigid structures similar to the concrete filled cells would be adequate for the purposes of the study. The decision was determined to be the appropriate procedure to address the reliability of these guard walls by the independent technical review team.

The concrete gravity monoliths guard walls were checked for stability against sliding, overturning, and bearing. Again, no factors of safety were used in the reliability analysis. This is the same analysis used for the concrete filled cell founded guard walls as well as other ORMSS gravity structures. The procedure is consistent with HQUSACE guidance.

The wooden pile founded guard wall at Montgomery Locks and Dam was analyzed for overturning about the top of the piles. Also, overturning at the rock foundation was computed because it was determined that the piles were spaced closely enough that they could effect sufficient skin friction to support the weight of soil between them. The piles themselves were checked for shear, bending, axial and combined bending-axial loads.

U.S. Army Corps of Engineers Louisville District

SUBJECT MARKLAND TYPICAL MONOLITH (R-81)

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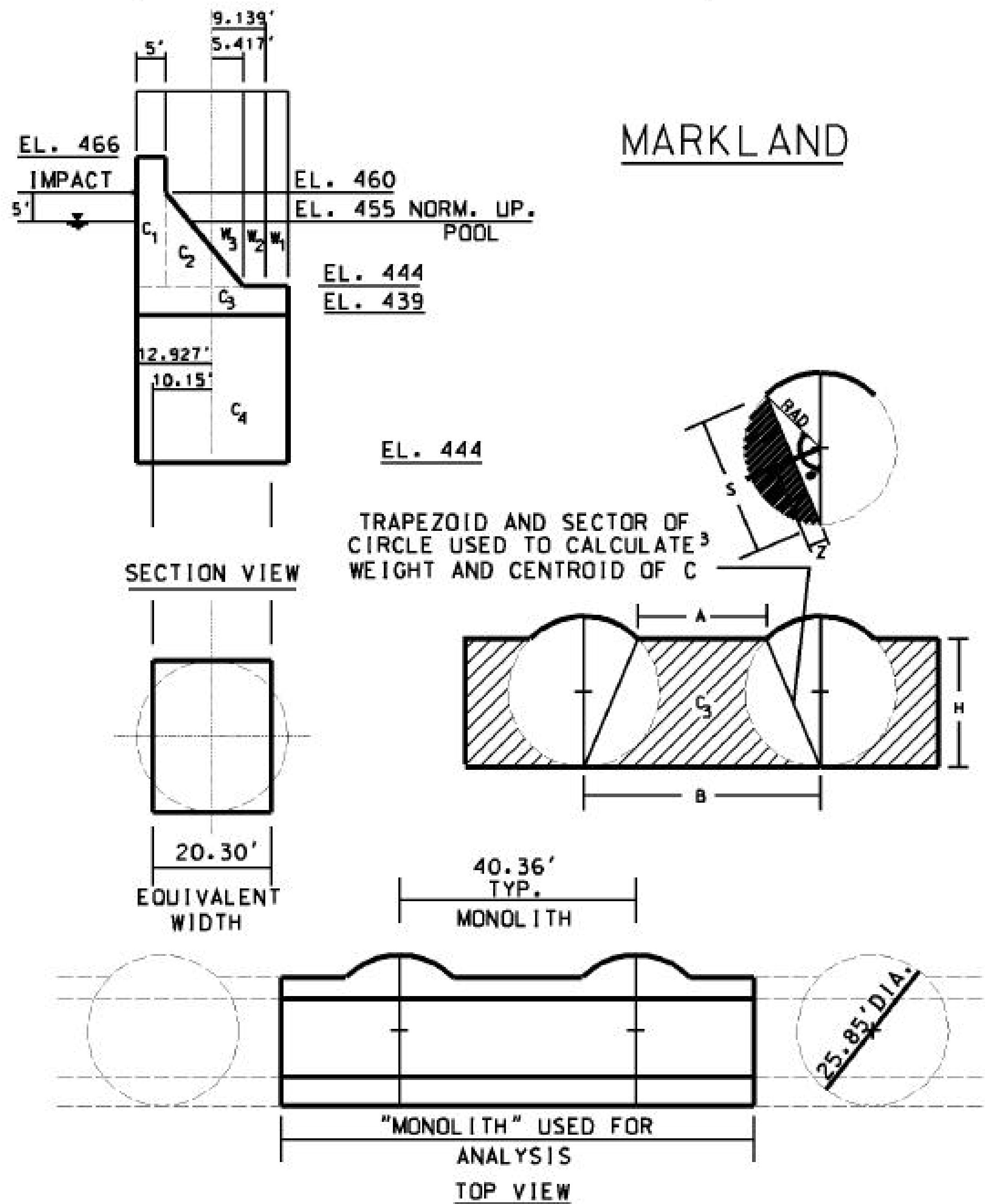

Figure 6.9.2.A. Markland Upper Guard Wall Plan and Section

6.9.3 Loading Assumptions

The major external loads that are experienced by approach walls are barge impact, hawser pull and soil loads (in the case of guide walls), with barge impact and soil loads being the most significant. Because barge impact loads are resisted by the passive wedge of the guide wall monoliths, it is highly improbable that any reasonable impact force could cause an unsatisfactory performance of a typical Ohio River guide wall.

The weight of the structure and three types of external loads are considered: soil, hydrostatic (lateral and uplift), and barge (impact and hawser pull) loads. Due to the wall being ported, water velocity through the ports is sufficient enough that siltation is generally not a problem on either side of the upstream guard walls. Thus, little to no silt build up is present. Additionally, siltation should be nearly equal on both sides effectively canceling any active driving forces. Therefore, lateral soil loads are neglected. Also because of the porting, head differentials in the upper approach should be less than 6" to 12" between the chamber and riverside of the guard wall. Therefore, lateral hydrostatic pressures are neglected. Because water is on both sides of the structure with minimal head differentials, full uplift is applied to the bottom of the cells regardless of the percentage of base in compression. Uplift is considered on the area of the guard wall that spans between the cells. Barge traffic can impose two oppositely directed loads, these being a barge impact upon lining up with the lock, and a hawser pull while tied off in the approach. Because hawser pull and barge impact are oppositely directed loadings from the same source only one of these loads can be applied to a monolith at a single instant. The model is therefore run for 20,000 iterations for each of the two independent load cases (impact and hawser pull). These loads are assumed to be applied at 5' above the upper pool level.

6.9.4 Random Variables and Constants in the Reliability Analysis

The random variables used for input in this model are for the foundation properties and barge impact forces. For the foundation properties, the strength parameters were based on information obtained from the as-built drawings, design memoranda, foundation reports, periodic inspection reports, and reference books. Cross sections, boring logs, N-values, and lab testing values were used to determine the range in strength values. All foundation and soil information was supplied by each district's geotechnical personnel. Very limited test values were available, thus, the values relied heavily on typical strength values published in reference books and original design information. Probabilistic values used in the reliability analyses included the type of distribution and maximum, minimum, mean, standard deviation, coefficient of variance, and correlation coefficient values. Unit weights and shear strength parameters (phi and c) were provided for all soil and rock materials. In addition, cross bed shear strengths and ultimate bearing capacity values were also provided for different rock layers. For the barge impact values, the means, standard deviations, and ranges for the impact and hawser forces to be used in the model were based on recommendations in the design guidance ETL 1110-2-321, discussions among the engineering team, and trial model runs. All the random variables used in this model are shown in Table 6.9.4.A. The values shown for the foundation strengths are representative of the Markland site. Other sites had similar data developed for their site-specific analysis.

The constants in the analysis were similar for other gravity models. The constants consisted of the unit weights of concrete and water, along with the upper pool level at each specific location. The values for Markland are shown in Table 6.9.4.B as an example.

Table 6.9.4.A. Random Variables for Markland Guard Wall Stability Model

Random Variables	Mean	Standard Deviation	Range Minimum	Range Maximum	Data Source
Rock – phi (deg)	38	4	35	45	1,7,8,9,10
Rock – c (psi)	20	20	0	25	1,7,8,9,10
Bearing Capacity (psi)	2083	208	1736	2430	1,7,8,9,10
Barge Impact (kips)	300	230	70	990	3,4,11,12
Hawser Pull (kips)	115	23	69	161	3,11,12

Table 6.9.4.B. Constants for Markland Guard Wall Stability Model

Constant	Value
Concrete Unit Weight (kcf)	0.1450
Water Unit Weight (kcf)	0.0624
Upper Pool Elevation (ft)	455.0

6.9.5 Reliability Model Computations

A Microsoft Excel™ spreadsheet was written to calculate the overturning, sliding and bearing factors of safety for the guard walls. This spreadsheet utilizes the @Risk™ add-on software, a program that uses the technique of Monte Carlo simulation for risk analysis. Uncertain input values such as external loads and material properties, are specified as probability distributions which describe the range of possible values for the input. The @Risk™ software replaces single values for each variable with the corresponding probability distribution for that variable. The spreadsheet is automatically recalculated a specified number of times (20,000 iterations) with the @Risk™ software choosing a new value for each variable from within the described probability distribution for that variable. The results of each iteration or calculation of the spreadsheet in terms of the factor of safety for each performance mode are computed by the model.

The vertical and horizontal components and the moments developed by the weight of the structure and applied external loads are calculated and summed. These values are used in the analyses to determine overturning and sliding stability and maximum base pressure. Overturning stability is simply calculated as the ratio of the righting moments to the overturning moments. To calculate bearing and sliding, the percentage of base in compression is first calculated using the calculated eccentricity (e) and using the equivalent rectangular width for B in the calculations. For bearing, the allowable bearing capacity is compared to the calculated maximum foundation pressure which is calculated accounting for the cases of full base in compression or less than 100% base in compression. For the case where the sum of resisting moments is less than the sum of the overturning moments (i.e. overturning failure), the percent of base in compression will be zero which results in both an overturning and bearing failure. However any iteration resulting in a calculated unsatisfactory performance for more than one mode will be counted for reliability purposes as one unsatisfactory performance for the structure. The shear friction sliding factor of safety is calculated in accordance with EM 1110-2-2200, for the simplified case of a single wedge sliding along a horizontal plane.

6.9.6 Results and Conclusions

Because of the original factors of safety used during design and the sound foundation at all of the sites where the analysis has been completed, no unsatisfactory performances were calculated in 20,000 iterations for any of the performance modes. These results are reasonable and expected since no significant movement of the guard wall has been noted since construction at any of the projects. The model is similar to other ORMSS gravity structure reliability models. An example of the spreadsheets used for the model can be seen in the miter gate sill reliability narrative, which is in Section 6.10. Therefore, the guard wall model sheets are not shown in this appendix. Additionally, since there were no unsatisfactory performances the economists did not need to run their analysis for the guard wall. Thus, the event tree is not included with this narrative.

6.9.7 References and Data Sources

1. Project Data - As-Built Drawings, Design Memoranda, Foundation Reports, Periodic Inspections
2. USACE ETL 1110-2-256 “Sliding Stability for Concrete Structures”
3. USACE ETL 1110-2-321 “Reliability Assessment of Navigation Structures Stability of Existing Gravity Structures”
4. USACE ETL 1110-2-338 “Barge Impact Analysis”
5. USACE EM 1110-2-2200 “Gravity Dam Design”
6. USACE M 1110-2-2503 “Design of Sheetpile Cellular Structures”
7. “Introduction to Rock Mechanics”, Second Edition, Richard E. Goodman, 1989. John Wiley & Sons
8. “Handbook on Mechanical Properties of Rocks”, Volume 1, V.S. Vutukuri, R.D. Lama & S.S. Saluja, 1974. Trans Tech Publications.
9. “An Introduction to Geotechnical Engineering”, Robert D. Holtz & William D Kovacs, 1981. Prentice-Hall, Inc.
10. “Foundation Analysis and Design”, Fourth Edition, Joseph E Bowles, 1988. McGraw-Hill, Inc.
11. “Ohio River Navigation System Report”, 1996.
12. Ohio River Main Stem Systems Study Meetings - Discussions, Personal Experience and Results of Preliminary Model Calibration.

6.10 MITER GATE SILL RELIABILITY

There are two basic types of miter gate sills on the Ohio River projects. These are unanchored concrete gravity sills and anchored concrete sills. The only sites will anchored miter gate sills are the upper three Ohio River projects. These projects are Emsworth, Dashields, and Montgomery (EDM) Locks and Dams. All other sites use unanchored concrete gravity sills, including J.T. Myers and Greenup. At the time of this interim report, only the results for the unanchored concrete miter gate sills have been completed (through calibrations, ITR, etc.). The anchored miter gate sills at EDM will be included as part of the final ORMSS report. Additionally, the unanchored miter gate sill results will be carried forward into the final ORMSS report. An example of a typical unanchored miter gate sill on a Ohio River project is shown in Figure 6.10.A. This photograph shows the auxiliary chamber miter gate sill at Markland Locks and Dam. In general, the sills of the main and auxiliary chamber are the same. Thus, the upper main chamber miter gate sill will be the same as the upper auxiliary chamber miter gate sill. The same holds true on the lower end relative to each chamber.

Figure 6.10.A. Photograph of Markland Auxiliary Chamber Miter Gate Sill

6.10.1 Reliability Model Description

The reliability model investigates the stability of each structure with random variables for input parameters, such as foundation shear strength, lower pool elevation, etc. Contrary to design calculations, reliability analysis looks only at the unsatisfactory performance of the structure. An unsatisfactory performance for a single iteration is constituted by a factor of safety less than 1.0 for any one or more of the performance modes. The performance modes selected for this mode are sliding of the structure, overturning, and bearing capacity failure of the foundation.

Because the structure is constructed of air-entrained concrete and is totally submerged, there is no effective concrete deterioration over time. The team only looked at normal and maintenance load cases, and not extreme events such as earthquakes and floods. Therefore, the reliability model is not considered to be time dependent such that the reliability degrades with time. A single probability of unsatisfactory performance is calculated for the model and used for every year in the economic analysis. This is consistent with HQUSACE guidance for reliability analysis of ORMSS gravity structure stability models.

6.10.2 Loading Assumptions

There are two types of unanchored miter gate sills used on the Ohio River. Those that are only used for the miter gates and others that are used as a combination miter gate sill and maintenance bulkhead sill. For the sills that only miter gate sills, a stability/reliability analysis was completed only for normal load cases. For combination sills, stability and reliability analyses were completed for both the normal and maintenance load cases. To see which sites have combination sills, please refer to the results shown in Table 6.10.5.A.

In general, calculations were based on current Corps of Engineers' lock design criteria. Full hydrostatic head is applied to the upstream and downstream faces and uplift on the base of the structure varies linearly from 100% of headwater to 100% of tailwater with no effect from foundation drains. In the case of the base not being entirely in compression, it is assumed a tension crack is formed and 100% of headwater pressure is applied along the length of the crack then the uplift varies linearly to tailwater from that point. All the sites with unanchored miter gate sills have miter gates that are horizontally-framed and therefore, the gates transfer no load to the sill and carry all the hydrostatic pressures above the top of the sill into the lock walls.

In recent analyses, sills at older locks were found to be unstable when analyzed using the current criteria. Since no failures of these structures has ever been observed in the Ohio River and Great Lakes Division, it was apparent that either the forces used in the analysis (primarily uplift) were overly conservative or there are additional resisting forces that had not been accounted for in design. To avoid computing an inappropriate number of unsatisfactory performances in the model, an external force resisting overturning was added to account for rock embedment. The model calculates this force as the passive cross-bed shear resistance of the rock wedge on the downstream face of the sill.

6.10.3 Random Variables and Constants Used in the Model

There were seven random variables used in the reliability model. Most of these were associated with rock strengths. An example of the supplied values for rock strengths for a typical Ohio River site is shown in Table 6.10.3.A. The values shown in the table are representative of the Markland project. These values were determined through boring logs from construction, design memoranda, reference material, and experience of the appropriate district's geotechnical personnel. The values were allowed to vary for each iteration of the analysis according to the distributions supplied. Additionally, CEWES-IM-DS compiled lower pool records for the years 1980 through 1995, inclusive, from Ohio River Navigation Center's Lock Performance Monitoring System (LPMS) data and produced a cumulative distribution histogram from which lower pool elevations were pulled for every iteration. The example histogram for Markland is shown in Figure 6.10.3.A. The horizontal axis in the figure is the daily elevation of the lower pool at Markland and the vertical axis is the number of times that the elevation occurred during the 16-year period. In the reliability analysis, lower pool values were allowed to vary for each iteration within the range of the histogram. Constant unit weights of concrete and water, 145 and 62.5 pounds per cubic foot, respectively, were used in the analysis. The upper pool was considered to be constant at elevation 455.0. This was determined using LPMS data over the same 16-year period. This is consistent with the majority of all lock and dams on the Ohio River.

Table 6.10.3.A. Material Properties for Markland Miter Gate Sill Stability Model

PROPERTY	DISTRIBUTION	MAXIMUM	MINIMUM	MEAN	STANDARD DEVIATION
Phi (degrees)	Normal	45	35	38	4
c (psi)	Normal	25	0	20	20
Unit Weight (pcf)	Normal	169.7	166	167.2	2
Cross-Bed Phi	Normal	57	37	47	4.5
Cross-Bed C (psi)	Normal	100	50	75	25
Ultimate Bearing Capacity (ksf)	Normal	350	250	300	30

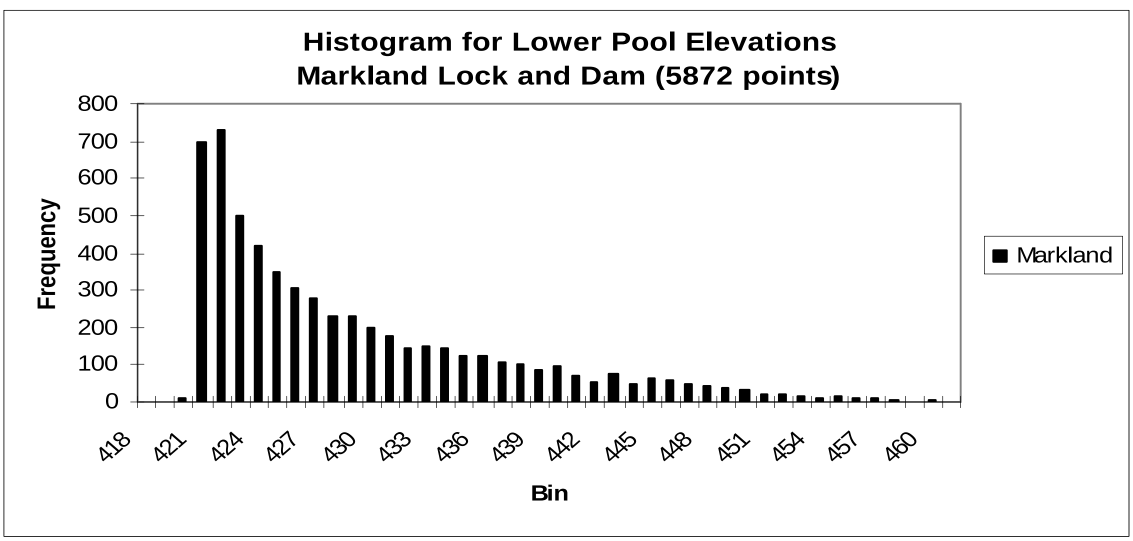

Figure 6.10.3.A. Lower Pool Elevation Histogram from 1980 through 1995

6.10.4 Reliability Model Computations

The miter gate sill stability reliability model consisted of a Microsoft Excel™ workbook and utilized the @Risk™ add-on to conduct a Monte Carlo simulation with random variables. The model was run for 20,000 iterations with a new set of random variables chosen by the @Risk™ software each iteration and the factors of safety for each performance mode were collected as output data. A Visual Basic macro was also set up to count the iterations and number of unsatisfactory performances and report them in a table. For each iteration and set of chosen random values, the model calculates the vertical and horizontal forces and respective moments. It then sums these values and uses an iterative process to determine the percent of the base in compression and final resultant location. Factors of safety are calculated based on these results and are recorded. This process is repeated for the entire simulation.

The overturning factor of safety is calculated by dividing the righting moments by the overturning moments. Any iteration with a factor of safety of overturning less than 1.0 is counted as an unsatisfactory performance. Sliding is first calculated by determining the horizontal friction along the base and comparing it to the sum of the horizontal forces. If this number is less than one, cross-bed shear resistance of the rock embedment is added using a wedge analysis. In this case, the model only determines if the sum of the shear capacities is greater than the horizontal forces, yielding a factor of safety greater than one, and doesn't calculate the exact factor of safety since we are only interested in numbers less than one. If the value is less than 1.0, then the iteration is counted as an unsatisfactory performance. The model also calculates the maximum foundation pressure and compares it to the random bearing capacity chosen for that particular iteration. Again, any value less than 1.0 causes an unsatisfactory performance for a particular iteration. For iterations that have multiple modes with values of factors of safety less than 1.0, the iteration is only counted as a one unsatisfactory performance in a computation of the probability of unsatisfactory performance. Thus, you can not have more than one unsatisfactory performance per iteration.

A copy of the model is provided at the end of overall Section 6.10 to give the reader a flavor of the model. The model is set up in several Microsoft Excel™ spreadsheets within one workbook for clarity. Copies of the individual sheets are supplied for reference in Figures 6.10.4.A through 6.10.4.C. Figure 6.10.4.A shows the *Input Sheet* for the model where the random variables and constants are input into the spreadsheet by the user. The *Computation Sheet* is where the basic stability computations are done for the section, random variable and constants from *Input Sheet* are used, and the factors of safety are computed for each iteration. The *Resistance Wedge Computation Sheet* is where the passive resistance forces are computed. Finally, the *Reliability Results Sheet* is where the unsatisfactory performances, iterations, and probabilities are tabulated for each simulation. The values shown within each figure depict typical values for Markland Locks and Dam. Other sites had the same type of data entered and analysis completed to determine their reliability.

6.10.5 Results and Conclusions

Since all of the Ohio River unanchored miter gate sills are either completely embedded into and/or founded on sound rock, no unsatisfactory performances were calculated in the simulation for any of the performance modes. These results are reasonable and expected since no movement of the sill has been noted at any of the projects since they were constructed. Since there were no unsatisfactory performances the economists did not need to run their analysis for the miter gate sill. Thus, the event tree for the miter gate sills is not included with this narrative. The results for all the runs are shown in Table 6.10.5.A.

Table 6.10.5.A. Unanchored Miter Gate Sill Reliability Results

@Risk runs of 20,000			
Project	Probability of Unsatisfactory Performance **Pf** (PUP)	Reliability **1-Pf**	Notes
Emsworth			1921-Anchored
Dashields			1929-Anchored
Montgomer			1936-Anchored
New	0	1	1961
Pike Island	0	1	1965
Hanniba	0	1	1972
Willow	0	1	1973
Bellevill *Normal*	0	1	1969
Bellevill *Maintenance*	0	1	1969
Racine *Normal*	0	1	1970
Racine *Maintenance*	0	1	1970
R.C. Byrd	0	1	1992-Without Account of
Greenup	0	1	1958
Meldahl	0	1	1962
Markland	0	1	1963
McAlpine	0	1	1961-Main Chamber
Cannelton *Normal*	0	1	1972
Cannelton *Maintenance*	0	1	1972
Newburgh *Normal*	0	1	1975
Newburgh *Maintenance*	0	1	1975
J.T. Myers *Normal*	0	1	1975
J.T. Myers *Maintenance*	0	1	1975
Smithland *Normal*	0	1	1980
Smithland *Maintenance*	0	1	1980
* Sills rely on anchors and will need a time dependent			

INPUTS		Source	Dist. Type	Mean	Std. Dev.	Min.	Max.
Upper Pool	455						
Lower Pool	425.5	CDF Lower Pool Sheet	CDF				
Base Elevation	388	Sections from LRL					
Top Elevation	405	Sections from LRL					
Base Width	23.5	Sections from LRL					
Length	1						
c	13.42	Shale and Limestone	Normal	20	20	0	25
phi	39.17	Shale and Limestone	Normal	38	4	35	45
Crossbed c	75.00	Shale and Limestone	Normal	75	25	50	100
Crossbed ϕ	47.00	Shale and Limestone	Normal	47	4.5	37	57
Top Rock U/S	402.00	Sections from LRL					
Top Rock D/S	405.00	Sections from LRL					
Unit Weight of Rock	0.17	Shale and Limestone	Normal	0.1672	0.002	0.166	0.1697
Bearing Capacity	300.00	Shale and Limestone	Normal	300	30	250	350

Figure 6.10.4.A. Input Sheet for Miter Gate Sill Stability Model

US Army Corps Of Engineers Ohio River Division	Subject MARKLAND LOCKS AND DAM LOWER MITER GATE SILL - AUXILARY	Page Of Pages
		Computed by Date
		Checked by Date

	Width	X	Height	X	Unit Wt.	X	Length			Vertical	Horizontal	Arm	Moments
			CONCRETE										
C1	23.5	X	8	X	0.145	X	1	X	1	27.26		11.750	320.31
C2	10	X	3	X	0.145	X	1	X	1	4.35		5.000	21.75
C3	6	X	6	X	0.145	X	1	X	1	5.22		20.500	107.01
C4	3	X	6	X	0.145	X	1	X	0.5	1.31		16.500	21.53
C5		X		X		X		X					
C6		X		X		X		X					
C7		X		X		X		X					
C8		X		X		X		X					
C9		X		X		X		X					
C10		X		X		X		X					
					Concrete Subtotal =					38.14			470.60
			MISC. VERTICAL										
W1	13.5	X	53	X	0.0625	X	1	X	1	44.72		16.750	749.04
W2	10	X	20.57	X	0.0625	X	1	X	1	12.86		5.000	64.28
			UPLIFT										
U1	23.5	X	31.57	X	0.0625	X	1	X	-1	(46.37)		11.750	(544.82)
U2	0	X	29.43	X	0.0625	X	1	X	-0.5	0.00		0.000	0.00
U3	23.5	X	29.43	X	0.0625	X	1	X	-1	(43.23)		11.750	(507.91)
			HYDROSTATIC										
H1	61	X	61	X	0.0625	X	1	X	-0.5		(116.28)	14.333	(1,666.70)
H2	31.57	X	31.57	X	0.0625	X	1	X	0.5		31.14	4.523	140.87
H3	50	X	50	X	0.0625	X	1	X	0.5		78.13	27.667	2,161.46
H4	20.57	X	20.57	X	0.0625	X	1	X	-0.5		(13.22)	17.856	(236.10)
			MISC. HORIZONTAL										
	Overturning Passive Rock Resistance												3,584.32
										Sum V 6.12	Sum H (20.23)		Sum M 630.72
													Sum Mr 4,773.01
													Sum Mo 557.97

INPUTS	
Upper Pool	455
Lower Pool	425.57
Base Elevation	388
Top Elevation	405
Base Width	23.5
Length	1
c	21.16
phi	41.20
Crossbed c	68.89
Crossbed ϕ	48.15
Top Rock U/S	402.00
Top Rock D/S	405.00
Unit Weight of Rock	0.169
Bearing Capacity	313.87

M/V =	103.13	ft.
e = M/V-B/2=	91.38	ft.
%Base in Compression =	0.0%	
Max. Found. Pressure=	313.87	ksf
Bearing Capacity=	313.87	ksf

Overturning F.S.=	8.554
Sliding F.S.=	1.000
Bearing F.S.=	1.000

Figure 6.10.4.B. Computation Sheet for Miter Gate Sill Stability Model

FS =	1.000
	1.000

Inputs

Crossbed c =	68.895
Crossbed ϕ =	48.145
rad =	0.840
Unit Weight of Rock =	0.169
c at Base =	21.161
ϕ at Base =	41.204
rad =	0.719
Top Rock U/S	402.00
Top Rock D/S	405.00
Upper Pool	455.00
Lower Pool	425.57
W1	44.719
W2	12.856
U1	-46.368
U2	0.000
U3	-43.226

Active Wedge	
α a =	-69.073
rad =	-1.206
Wa =	6.330
Va =	17.734
Ua =	56.208
La =	14.989
Pa =	52.203

Sum =	1065.972

Passive Wedge	
α p =	20.927
rad =	0.365
Wp =	63.820
Vp =	57.151
Up =	86.471
Lp =	47.594
Pp =	1018.070

Structure Wedge	
α s =	0.000
rad =	0.000
Ws =	38.135
Vs =	57.575
Us =	89.594
Ls =	0.000
Hl-Hr =	9.656
Ps =	-4.301

Overturning Passive Wedge

α =	20.9275
rad =	0.3653
W =	27.2659
N =	25.4673
T =	9.7390
R =	427.0171
arm =	8.3939
M =	3584.3242

Figure 6.10.4.C. Resistance Wedge Computation Sheet for Miter Gate Sill Stability Model

6.11 SUMMARY OF ENGINEERING RELIABILITY RESULTS

Engineering reliability models have been developed for major lock components for the J.T. Myers/Greenup Interim Report. As part of this development, the engineering team developed hazard functions for time dependent components and probabilities of unsatisfactory performance values for non-time dependent components. This was done in an effort to determine no only the maximum useful life of major lock components, but also to address the potential impacts of these components if they fail to perform in a satisfactory manner. All components that were to have reliability analyses completed for them for J.T. Myers and Greenup have been completed as of this interim report (runs made, economic analysis completed, reviewed, etc.). There are several components at other project sites that have been completed, however, there remains more runs and subsequent economic analysis for components that have not been completed. The remaining lock model runs and economic analysis will be completed as part of the final ORMSS report. Additionally, reliability models will be developed for major dam components to determine their future economic impacts to the Ohio River system. This will also be done as part of the ORMSS final report. This section addresses the results to date for all models as well as required future work. Components that were economically justified before 2020 had an additional economic analysis performed on them to “fine tune” the replacement date.

6.11.1 J.T. Myers Lock Component Engineering Reliability Results

All the lock components have had reliability and economic analyses completed for them at J.T. Myers. The dam components will be completed as part of the final ORMSS report. The economic results of the engineering reliability for the J.T. Myers lock components are shown in Table 6.11.1.A for both the main and auxiliary chamber.

As shown in the table, there are five individual justified component replacements for J.T. Myers during the study period. The main chamber components economically justified for replacement are the hydraulic system in 2020 and the vertically-framed culvert valves in 2030. The auxiliary components justified are the vertically-framed culvert valves, hydraulic system, and the electrical system. The auxiliary chamber components are all timed for replacement in the year 2030. The replacement dates are all the lowest average annual cost when compared to the fix-as-fails scenario and other replacement dates. The exception to this is the analysis for the electrical and hydraulic systems. The results for these components yielded lower average annual costs as the replacement date was continually pushed out into the future. After reviewing the economic and engineering analysis, the study team decided that this was mainly a function of the event tree and hazard rates. Knowing the limits of the analysis with the mechanical and electrical models, plus funding and schedule restrictions, the economists and engineers decided to set the timed replacement for these components at the first replacement date where the average annual costs falls below the fix-as-fails scenario. These all fell at the year 2030 when the components will be approximately 60 years old. This seemed to yield accurate results within the confines of the analysis itself.

Table 6.11.1.A. J.T. Myers Lock Component Reliability Results

J.T. Myers Main Chamber Engineering Reliability Results											
All Costs x $1,000											
	Lock Wall Monoliths			HF Miter	Guard	Miter Gate	VF Culvert	Electrical	Miter Gate	Valve	Hydraulic
	Middle Wall	River Wall	MG Mono	Gates	Wall	Sills	Valves	System	Machinery	Machinery	System
Run Date	n/a	n/a	n/a	22-Feb-99	n/a	n/a	26-Jul-99	29-Mar-99	6-Apr-99	6-Apr-99	6-Apr-99
Fix-As-Fails	No Failures	No Failures	No Failures	**45.0**	No Failures	No Failures	274.7	**904.5**	**45.2**	**64.7**	4,169.5
Replace in:											
2000							433.1	2,128.8	2,128.8	361.7	6,760.1
2010							249.3	1,664.2	1,545.9	196.7	4,546.1
2020							190.7	1,398.5	1,150.1	120.5	**3,640.5**
2025											
2030				854.3			**172.9**	1,209.9	823.9	79.7	2,778.8
2035											
2040				821.9			195.4	1,304.1	813.8	66.8	2,340.7
2045											
2050				914.5							

J.T. Myers Auxiliary Chamber Engineering Reliability Results											
All Costs x $1,000											
	Lock Wall Monoliths			HF Miter	Guide	Miter Gate	VF Culvert	Electrical	Miter Gate	Valve	Hydraulic
	Middle Wall	Land Wall	MG Mono	Gates	Wall	Sills	Valves	System	Machinery	Machinery	System
Run Date	n/a	n/a	n/a	n/a	n/a	n/a	26-Jul-99	29-Mar-99	6-Apr-99	6-Apr-99	6-Apr-99
Fix-As-Fails	No Failures	No Failures	No Failures	No Failures	No Failures	No Failures	435.5	99.6	1.5	2.4	95.2
Replace in:											
2000							333.6	408.8	408.8	231.2	282.8
2010							197.0	227.2	215.6	124.5	159.7
2020							130.7	145.4	122.4	75.7	102.6
2025											
2030							**92.3**	**98.0**	63.4	39.8	**70.4**
2035											
2040							175.0	81.6	38.9	27.2	65.9
2045											
2050											

Given the replacement dates, the engineering team then had to go in and place replacement closures and associated repair costs into the cost and closure matrices for the J.T. Myers project. Using the scheduled replacement values for each component that were supplied to the economists in the event trees, the team projected a 60 day closure of the main chamber in 2020 for the replacement of the hydraulic system at a cost of $2,115,000. Because the main chamber operates on four valves, it is possible to replace all four valves without actually closing the lock chamber. Therefore, a 90-day period of half-speed operation for the main lock at a cost of $2,800,000 was input into the main chamber matrix in 2030. The $2,800,000 cost again was pulled from the main chamber culvert valve event tree for scheduled replacement of four main chamber culvert valves. For the auxiliary chamber, all three components (vertically-framed culvert valves, hydraulic system, and electrical system) required replacement around 2030. The engineering team assumed that savings with respect to closure time and repair cost would occur by replacing the electrical and hydraulic systems during a single 60 day closure in the year 2030. A replacement cost of $3,642,000 was also entered into the matrix in the year 2030 for the auxiliary chamber. By combining the closures, the closure time was reduced from 75 days to 60 days. Additionally, the repair cost was reduced from $3,942,000 to $3,642,000, a savings of $500,000 over individual replacements. The auxiliary chamber vertically-framed culvert valves were assumed replaced in 2031 at a cost of $1,400,000. Because the replacement cost of all three items together would not meet current major rehabilitation threshold, rolling all the closures together into a major rehabilitation was not investigated for the auxiliary chamber at J.T. Myers. Refer to Section 7 of this General Engineering Appendix to review the cost and closure matrices for J.T. Myers.

In addition to the projected replacement closures, there are some components that are not necessarily justified for replacement but still have both a repair and navigation delay cost associated with their chance of unsatisfactory performance. A prime example of this would be the main chamber miter gates at J.T. Myers. The main chamber miter gates have an average annual cost of $45,000 associated with their chance of unsatisfactory performance under the fix-as-fails scenario. However, replacing them ahead of failure is not justified due to the required lengthy chamber closure time and repair costs. Therefore, no replacement of the main chamber miter gates is input into the matrix; however, the costs associated with the probability of unsatisfactory performance ($45,000 average annual) are included in the overall economic analysis in both the With and Without Project conditions. For the Without Project condition (no extended auxiliary chamber where there is a single 1200-ft lock and one 600-ft auxiliary chamber at the site), if the existing main chamber miter gates fail to perform satisfactorily, there is both a significant navigation delay cost and repair cost associated with repairing them. The major navigation delay cost comes from having the main chamber closed for miter gate repairs and double-cutting tows through the shorter auxiliary chamber. However, under the With Project condition (an extended auxiliary lock chamber that provides two 1200-ft chambers at the site), a "failure" of the existing main chamber miter gates after the existing auxiliary chamber is extended would not cause much, if any, navigation delay cost because there is another 1200-ft chamber to serve navigation. Thus, barges would not need to double cut to process through the newly extended lock chamber. The navigation delay costs are essentially eliminated for the With Project condition but remain in the Without Project condition. For simplicity, it is assumed that the repair costs would not change for either the With or Without Project condition.

This type analysis is assumed to hold true for all components that are not economically justified for individual replacement. It also holds true for the time from the start of the study period (the year 2000) until the date that a component is replaced. For example, the main chamber vertically-framed culvert valves are most economically justified for replacement in the year 2030. Therefore, the proper cost and closure time is input into the J.T. Myers matrix in 2030 for main chamber valve replacement. Additionally, the fix-as-fails average annual cost must be included in the economic analysis for the years 2000 through 2029 because the valves are not replaced until 2030 in the matrices. The differences between the With and Without Project conditions would hold true for the valves once the existing auxiliary chambers is extended in the economic analysis.

6.11.2 Greenup Lock Component Engineering Reliability Results

All the lock components have had reliability and economic analyses completed for them at Greenup. The dam components will be completed as part of the final ORMSS report. The economic results of the engineering reliability for the Greenup lock components are shown in Table 6.11.2.A for both the main and auxiliary chamber.

As shown in the table, there are three individual justified component replacements for Greenup. The main chamber component economically justified for replacement is the horizontally-framed miter gates in 2004. Because this component requires early replacement, in regards to the study period, the economic analysis was fine tuned to determine the optimum year between 2000 and 2005 to replace the main chamber miter gates. The auxiliary components justified are the horizontally-framed miter gates in 2035 and the electrical system in 2030. The replacement dates are all the lowest average annual cost when compared to the fix-as-fails scenario and other replacement dates.

Table 6.11.2.A. Greenup Lock Component Reliability Results

Greenup Main Chamber Engineering Reliability Results											
All Costs x $1,000											
	Lock Wall Monoliths			HF Miter	Guard	Miter Gate	HF Culvert	Electrical	Miter Gate	Valve	Hydraulic
	Middle Wall	River Wall	MG Mono	Gates	Wall	Sills	Valves	System	Machinery	Machinery	System
Run Date	n/a	n/a	n/a	22-Feb-99	n/a	n/a	29-Mar-99	29-Mar-99	5-Apr-99	5-Apr-99	5-Apr-99
Fix-As-Fails	No Failures	No Failures	No Failures	8,718.8	No Failures	No Failures	**26.9**	**903.2**	**26.6**	**35.7**	**625.8**
Replace In:											
2000				1,375.8			439.7	1,127.9	1,128.0	369.9	4,172.6
2001				1,353.9							
2002				1,332.4							
2003				1,323.0							
2004				**1,317.6**							
2005				1,332.2							
2010				2,084.4			227.1	1,229.2	1,073.1	197.6	4,250.7
2020							121.2	1,130.1	805.7	113.4	3,146.5
2030							64.6	1,048.4	580.8	71.5	2,246.8
2040							36.5	1,083.1	500.4	52.5	1,822.7
2050											

Greenup Auxiliary Chamber Engineering Reliability Results											
All Costs x $1,000											
	Lock Wall Monoliths			HF Miter	Guide	Miter Gate	VF Culvert	Electrical	Miter Gate	Valve	Hydraulic
	Middle Wall	Land Wall	MG Mono	Gates	Wall	Sills	Valves	System	Machinery	Machinery	System
Run Date	n/a	n/a	n/a	1-Mar-99	n/a	n/a	29-Mar-99	29-Mar-99	5-Apr-99	5-Apr-99	5-Apr-99
Fix-As-Fails	No Failures	No Failures	No Failures	269.3	No Failures	No Failures	No Failures	227.6	**1.7**	**3.0**	**38.3**
Replace In:											
2000				645.0				397.1	397.1	219.5	247.8
2010				338.8				258.1	206.7	115.7	139.6
2020				172.1				207.3	107.2	61.0	91.6
2030				94.0				**194.9**	58.5	35.4	70.3
2035				**80.8**							
2040				87.2				207.3	43.9	32.7	84.9
2045				120.6							
2050				173.9							

Given the replacement dates as indicated in the table, the engineering team then had to go in and place replacement closures and associated repair costs into the cost and closure matrices for the Greenup project. Because the miter gates were the component that required replacement, the necessary costs for both the upper and lower sets of gates along with installation time pushed the total replacement cost of the major rehab threshold, which is currently approximately $9.5 million. Therefore, a major rehab of the main chamber was placed into the main chamber at Greenup in the years 2004 and 2005. This rehab is for the replacement of the upper main chamber miter gates and emergency gate in the year 2004 and the lower main chamber miter gates in 2005. Although the emergency gate was not one of the components requiring reliability analysis at Greenup, they are in such poor shape at Greenup they need to be replaced.

The auxiliary chamber components requiring replacement are the miter gates in the year 2035 and the electrical system in 2030. The combination of these two also push the replacement cost over the major rehabilitation threshold; therefore, a major rehab of the auxiliary chamber has been placed into the matrix at Greenup in the years 2030 and 2031. For reference, please refer to the Greenup cost and closure matrices provided in Section 7 of this General Engineering Appendix.

6.11.3 Lock Component Reliability Results for Other ORMSS Projects

Reliability results are available for lock components at several other Ohio River projects, however, there are no other sites outside of J.T. Myers and Greenup that have all the lock component's reliability analyses completed. This was part of the agreement between the engineering team and ORMSS economists in order to meet the deadline for this interim report. For the interim report, the engineering team was required to complete the reliability analysis for all lock components only at J.T. Myers and Greenup. As part of the overall reliability model development, other sites were able to have some of their respective analyses completed in time for this interim report. A summary of what has been completed for sites other than J.T. Myers and Greenup is shown in Table 6.11.3.A. The remaining lock reliability analyses not yet finished will be completed for the final ORMSS report. Note that all dam reliability models will be completed as part of the final ORMSS report. This includes tainter dam gates, vertical lift dam gates, and dam gate anchorages.

The table should be fairly easy to follow. Cells that have been left empty indicate that the analysis has not yet been completed. Cells with "n/a" mean than the component is not located at a particular project or chamber. Cells with the term " No Failures" indicate that a reliability analysis was completed for the component, but there were no failures encountered during the study period. Cells with the term "Fix-As-Fails" indicate that an analysis was completed with failures, however, a replacement was not economically justified. Finally, cells with a projected year in them show the economically justified replacement date for that component.

As shown in the table, a vast majority of the non-time dependent gravity structures (guard walls, guide walls, lock walls, and miter gate sills) have been completed. Additionally, most of the horizontally-framed miter gate runs have been finished. The vertically-framed miter gates for EDM have been completed. The majority of the remaining lock reliability work is for electrical and mechanical models. The electrical system reliability analysis has only been completed at J.T. Myers, Greenup, and Markland. The same is true for the miter gate machinery, culvert valve machinery, and hydraulic system. Additional work remains on the anchored gravity structures at EDM, as well as the vertically-framed culvert valve reliability analyses.

Table 6.11.3.A. Lock Reliability Results at Time of Interim Report for All Sites except J.T. Myers and Greenup

Lock Engineering Reliability Model Economic Results At Time of ORMSS Interim Report													
ORMSS Project	Lock Chamber	VF Miter Gates	HF Miter Gates	VF Culvert Valves	HF Culvert Valves	Land Lock Wall	Middle Lock Wall	River Lock Wall	Guide Wall	Guard Wall	Miter Gate Sill	Electrical System	Miter Gate Machinery
Emsworth	Main	No Failures	n/a	n/a	n/a								
	Auxiliary	n/a	No Failures	n/a	n/a								
Dashields	Main	No Failures	n/a	n/a	n/a								
	Auxiliary	n/a	No Failures	n/a	n/a								
Montgomery	Main	No Failures	n/a	n/a	n/a								
	Auxiliary	n/a	No Failures	n/a	n/a								
N.Cumberland	Main	n/a	2015	n/a		n/a			n/a		No Failures		
	Auxiliary	n/a		n/a				n/a	No Failures	n/a	No Failures		
Pike Island	Main	n/a	2025	n/a		n/a			n/a	No Failures	No Failures		
	Auxiliary	n/a	Fix-As-Fails	n/a				n/a	No Failures	n/a	No Failures		
Hannibal	Main	n/a			n/a	n/a	No Failures	No Failures	n/a	No Failures	No Failures		
	Auxiliary	n/a			n/a	No Failures	No Failures	n/a	No Failures	n/a	No Failures		
Willow Island	Main	n/a	2040		n/a	n/a			n/a	No Failures	No Failures		
	Auxiliary	n/a	No Failures		n/a			n/a	No Failures	n/a	No Failures		
Belleville	Main	n/a	2030		n/a	n/a	No Failures	No Failures	n/a	No Failures	No Failures		
	Auxiliary	n/a			n/a	No Failures	No Failures	n/a	No Failures	n/a	No Failures		
Racine	Main	n/a	2040		n/a	n/a			n/a	No Failures	No Failures		
	Auxiliary	n/a			n/a			n/a	No Failures	n/a	No Failures		
R.C. Byrd	Main	n/a	No Failures		n/a	n/a	No Failures	No Failures	n/a	No Failures	No Failures		
	Auxiliary	n/a	No Failures		n/a	No Failures	No Failures	n/a	No Failures	n/a	No Failures		
Meldahl	Main	n/a	2008	n/a		n/a			n/a	No Failures	No Failures		
	Auxiliary	n/a	2040	n/a				n/a	No Failures	n/a	No Failures		
Markland	Main	n/a	2001	n/a	2005	n/a	No Failures	No Failures	n/a	No Failures	No Failures	Fix-As-Fails	Fix-As-Fails
	Auxiliary	n/a	2025	n/a	2030	No Failures	No Failures	n/a	No Failures	n/a	No Failures	Fix-As-Fails	Fix-As-Fails
McAlpine	Exist Main	n/a	n/a	n/a		n/a	No Failures	No Failures	n/a	No Failures	No Failures		
Cannelton	Main	n/a	2030		n/a	n/a	No Failures	No Failures	n/a	No Failures	No Failures		
	Auxiliary	n/a	Fix-As-Fails		n/a	No Failures	No Failures	n/a	No Failures	n/a	No Failures		
Newburgh	Main	n/a	Fix-As-Fails		n/a	n/a	No Failures	No Failures	n/a	No Failures	No Failures		
	Auxiliary	n/a	No Failures		n/a	No Failures	No Failures	n/a	No Failures	n/a	No Failures		
Smithland	Land	n/a	2030		n/a	No Failures	No Failures	n/a		n/a	No Failures		
	River	n/a	2030		n/a	n/a	No Failures	No Failures	n/a		No Failures		

Table Notes: "No Failures" indicates that the engineering reliability model was run but there were no failures encountered in the analysis

"Fix-As-Fails" indicates there were failures computed from the reliability model, but no justified replacement of component

Cells with dates indicate the economically justified replacement year for a particular component

An empty cell indicates that the reliability model has not been run for a particular component

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SECTION 7

COST AND CLOSURE MATRICES FOR J.T. MYERS AND GREENUP PROJECTS

7.1 GENERAL

This section describes the cost and closure matrices used in the formulation process for both projects. The cost and closure matrices are a series of spreadsheet matrices that detail lock chamber specific costs, closures, and other project costs for the time frame 2000 through 2060. The matrices are used to project future lock chamber closures and costs in order to perform a complete economic analysis.

7.2 OVERVIEW OF MATRICES

The cost and closure matrices can be broken into four separate sections: main chamber closures and costs, auxiliary chamber closures and costs, other project costs, and the summary information section. The without project baseline and status quo maintenance scenario matrices for both JT Myers and Greenup are shown at the end of this Tab. A description of each portion of the matrix is supplied in the following paragraphs.

Main Chamber Closures and Costs. In this portion of the matrix, a short, one-line description of the work item is supplied to track the type of closure. Additionally, the different types of closures are projected, along with associated costs, in the matrix with the description of work. See Section 7.3 for a description of the types of chamber closures. Closure times are based upon historical performance associated with these types of closures in the past. For example, it is known for the JT Myers site that 45-day maintenance dewatering closures occur about every 15 years on average. It is also known that for the major dewaterings, the Louisville District's repair fleet costs approximately $35,000 per day, which includes costs for all labor, equipment, material, etc. Therefore, the repair cost was simply determined by multiplying the cost per day by the number of days of closure-related work. The costs and closures for the Greenup matrices were also developed in a similar manner according to their historic fleet costs and associated repair times.

Auxiliary Chamber Closures and Costs. This section of the matrix is the same as the main chamber, but the maintenance schedule and projected replacement dates, etc, are different because the chamber sees considerably less traffic than the main chamber. The process of how the costs and closures were developed was the same as for the main chamber.

Other Project Costs. In order to determine the overall cost to operate the project, other major costs had to be captured in the matrix. Included in these costs are items such as operations and maintenance (O/M) costs, engineering reliability-based costs, dam repair costs, and dredging costs.

The O/M costs were developed by tracking the 5-year operational costs of the project from 1991-1995 and inflating them to current levels. O/M costs covered include all project site labor, overhead, equipment, and minor maintenance (which includes project contracts such as grass mowing and minor painting).

The engineering reliability-based costs (LCLM cost columns in the matrix) track both the repair and navigation delay costs associated with major lock components that were not justified for replacement based upon the reliability analysis. This information is obtained from the output from the economic model developed to analyze the impacts of major lock and dam probabilities of failures developed by the engineering team relative to average annual costs. The economic model is termed the Life Cycle Lock Model (LCLM) analysis and was created to specifically link engineering reliability to the economic analysis. The LCLM costs in the matrix are broken into two categories. The first is the repair cost, which considers only the costs to repair the “failed” component. Navigation delay costs are captured under the transportation delay column.

Dam costs are projected for only work such as replacement of dam gates. Because most major maintenance is performed on the lock and only lock related work typically impacts navigation, it was decided to only track major costs associated with the dam. Therefore, dam gate replacement costs are the only dam costs placed in the matrix. For this interim report, it was assumed that dam gates would need to be replaced at after about 75 years of service unless a particular site warranted earlier replacement. For the final ORMSS Report, dam gate replacements will be justified using reliability analyses in a similar manner as done for lock components.

Dredging costs were obtained for the years 1991-1995 and projected at current level prices. Only dredging in the approaches at the project site was considered to be direct costs to the project.

Summary Information. The summary section simply sums up annual closures for both the main and auxiliary chamber. Additionally, annual costs are summed up for the project.

7.3 TYPES OF CLOSURES

Closure of either an auxiliary or main chamber at a site can occur for a variety of reasons. Some closures are related to level of maintenance previously performed on the lock chamber, while others are not affected by maintenance history. For the purposes of this study, chamber closures were broken down into five categories. The five categories of closures are **Cyclical Maintenance**, **Unscheduled Maintenance**, **Random Minor**, **Component Replacement**, and **Major Rehabilitation**. A description of each will be provided, along with how these closures were scheduled in the matrices.

Cyclical Maintenance. These types of scheduled closures are generally due to inspection and required maintenance work on the major components of a lock (miter gates, culvert valves, emergency gates, etc.). Generally, cyclical maintenance includes dewatering the chamber for inspection and major repair work. Cyclical maintenance schedules vary between districts according to their fleet size, method of operation, lock usage and overall number of lock chambers requiring maintenance within their boundaries, but generally run in 15-year cycles. Work performed under this type of closure is considered preventative maintenance, in the sense that the cyclical repairs help to ensure proper operation and performance of the lock chamber major components. This work would include such things as jacking the miter gates to replace pintles, bushing, seals, etc, repair work on culvert valves, clearing of lateral ports, and other major types of repairs to components that typically operate underwater. These schedules were determined by investigating historical cyclical maintenance patterns and developing a future schedule according to the each district's Operations Division current policy for each district.

Unscheduled Maintenance. This type of closure is for failures of major components under the baseline maintenance scenario, where components are only replaced after they fail. These closures are considered reactive, rather than preventative. The Corps of Engineers has always taken a preventative approach to maintaining their projects on the Ohio River in order to limit the number of reactive, or unscheduled, maintenance closures. These closures were projected into the baseline condition using a combination of engineering reliability and engineering judgment for major lock components.

Random Minor. These closures are independent of maintenance or replacement/rehabilitation work. These involve down time due to items that are considered unavoidable. Lock chambers are sometimes closed for unforeseen occurrences regardless of historical level of maintenance. Examples of this type of closure would be equipment malfunction that can easily be repaired within a couple of days or repair of miscellaneous items such as floating mooring bits or wall armor. Random minor closures do not include closure time due to weather-related incidents, debris, accidents, or interference caused by other vessels. These closures are being handled by reducing the effective capacity of the chamber in the delay curves used in economic modeling. This information was obtained by utilizing the existing database developed by an A/E for the Corps of Engineers for all Ohio River lock chambers. The A/E conducted an exhaustive search of all closures over eight hours long for all Ohio River locks. This included searching through maintenance records at each district and project site. Also, the project logbooks at each site were reviewed to gather this information.

Component Replacement. As the projects age (most of the projects will be nearly 100 years old by the year 2060) many of the major components will need to be replaced in order to keep the chamber usable for passing traffic. History indicates that items such as miter gates, culvert valves, etc., tend to need replacement after about 50 or 60 years of operation. This obviously varies depending upon site specific conditions, original design parameters, and traffic levels.

Engineering reliability models have been developed for all the major lock components at each site to determine when they reach the end of their serviceable life. The reliability models will only address types of failure that would prompt the need for either major repairs or component replacement. The reliability models are attempting to address failure mechanisms that are not addressed by routine maintenance, such as fatigue life and loss of strength due to corrosion. Therefore, the results of the reliability models are not affected by cyclical maintenance. The reliability models will yield an annual hazard rate (hazard function) that determines the probability that a component will fail given that it has survived up to that point in time. Cyclical maintenance tends to address general "wear and tear" items that are readily replaceable during maintenance dewaterings (pintles, seals, quoin blocks, etc.) not fatigue/corrosion problems.

Individual component hazard rates were input into the LCLM economic model, along with component-specific event trees to determine if the components were economically justified for replacement. The LCLM results yielded annual average cost due to navigation delay and component repair/replacement for different replacement dates of particular components, along with costs associated with a fix-as-fails policy. This was done for all components for which reliability models were developed. The results from the different replacement dates were compared to one another to determine the date during the study period that yields the lowest average annual cost for that component. If the fix-as-fails costs were the lowest, then the component was not justified for replacement and the fix-as-fails costs were added to the matrix. For components that were justified for replacement, the cost to manufacture the component and ship it to the site, in addition to the closure time required to install the component, were placed in the matrix. In addition, fix-as-fail costs for components that were justified for replacement were added into the matrix up until the year the component was replaced in the matrix.

Major Rehabilitation. This type of closure was developed from the component replacement schedule for a site described above. Once replacement dates for all the components are projected with the LCLM in the steps described above, it may prove more beneficial to combine replacement of several of the components together in one or two closures and call it a major rehabilitation. If projected replacement dates for several components are near the same time frame, it would be more economical to replace several components during consecutive closures to limit the delay to navigation.

TABLE 7-1. Baseline Scenario Closures & Costs (thousands of 1999$) -- J.T. Myers

			Main Closure Days					Main Chamber Costs								Auxiliary Closure Days					Auxiliary Chamber Costs						Other Project Costs					
			Unsch. Closures		Scheduled Closures			Unsch. Closures		Scheduled Closures						Unsch. Closures		Scheduled Closures			Unsch. Closures		Scheduled Closures				Annual	LCLM Costs				
Year	Main. Item	F/E 1/2-speed	Unsch. Main.	Random Minor	Cyc. Main.	Comp. Repl.	Major Rehab.	Unsch. Main.	Random Minor	Cyc. Main.	Comp. Repl.	Major Rehab.	Total Costs	Main. Item	F/E 1/2-speed	Unsch. Main.	Random Minor	Cyc. Main.	Comp. Repl.	Major Rehab.	Unsch. Main.	Random Minor	Cyc. Main.	Comp. Repl.	Major Rehab.	Total Costs	O&M Costs	Repair	Trans. Delay	Dam Cost	Dredge Costs	Total Costs
2000	Inspection	-	-	-	15	-	-	$ -	$ -	$ 525	$ -	$ -	$ 525	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 46	$ 437	$ -	$ 156	$ 2,988
2001	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	5	-	-	-	$ -	$ 100	$ -	$ -	$ -	$ 100	$ 1,824	$ 53	$ 513	$ -	$ 156	$ 2,646
2002	-	-	-	5	-	-	-	$ -	$ 100	$ -	$ -	$ -	$ 100	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 49	$ 495	$ -	$ 156	$ 2,624
2003	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	Mgate Paint	-	-	-	45	-	-	$ -	$ -	$ 2,100	$ -	$ -	$ 2,100	$ 1,824	$ 52	$ 571	$ -	$ 156	$ 4,703
2004	MG & Appr. Wall	-	-	-	60	-	-	$ -	$ -	$ 2,490	$ -	$ -	$ 2,490	Maint Dewater	-	-	-	45	-	-	$ -	$ -	$ 1,868	$ -	$ -	$ 1,868	$ 1,824	$ 56	$ 613	$ -	$ 156	$ 7,007
2005	Mgate Paint	-	-	-	45	-	-	$ -	$ -	$ 2,100	$ -	$ -	$ 2,100	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 61	$ 676	$ -	$ 156	$ 4,817
2006	Maint Dewater	-	-	-	45	-	-	$ -	$ -	$ 1,868	$ -	$ -	$ 1,868	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 60	$ 675	$ -	$ 156	$ 4,583
2007	-	-	-	5	-	-	-	$ -	$ 100	$ -	$ -	$ -	$ 100	-	-	-	5	-	-	-	$ -	$ 100	$ -	$ -	$ -	$ 100	$ 1,824	$ 64	$ 804	$ -	$ 156	$ 3,048
2008	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 63	$ 859	$ -	$ 156	$ 2,902
2009	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 65	$ 954	$ -	$ 156	$ 2,999
2010	-	-	-	10	-	-	-	$ -	$ 200	$ -	$ -	$ -	$ 200	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 69	$ 1,091	$ -	$ 156	$ 3,340
2011	Inspection	-	-	-	15	-	-	$ -	$ -	$ 525	$ -	$ -	$ 525	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 64	$ 955	$ -	$ 156	$ 3,524
2012	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	Inspection	-	-	-	15	-	-	$ -	$ -	$ 525	$ -	$ -	$ 525	$ 1,824	$ 73	$ 1,281	$ -	$ 156	$ 3,859
2013	-	-	-	1	-	-	-	$ -	$ 20	$ -	$ -	$ -	$ 20	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 74	$ 1,287	$ -	$ 156	$ 3,361
2014	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	1	-	-	-	$ -	$ 20	$ -	$ -	$ -	$ 20	$ 1,824	$ 78	$ 1,408	$ -	$ 156	$ 3,486
2015	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 81	$ 1,575	$ -	$ 156	$ 3,636
2016	Inspection	-	-	-	15	-	-	$ -	$ -	$ 525	$ -	$ -	$ 525	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 79	$ 1,622	$ -	$ 156	$ 4,206
2017	-	-	-	10	-	-	-	$ -	$ 200	$ -	$ -	$ -	$ 200	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 81	$ 1,712	$ -	$ 156	$ 3,973
2018	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 87	$ 1,862	$ -	$ 156	$ 3,929
2019	Hydraulic Failure	-	90	-	-	-	-	$ 3,803	$ -	$ -	$ -	$ -	$ 3,803	Maint Dewater	-	-	-	45	-	-	$ -	$ -	$ 1,868	$ -	$ -	$ 1,868	$ 1,824	$ 88	$ 2,048	$ -	$ 156	$ 9,787
2020	Hydr. System	-	-	5	-	60	-	$ -	$ 100	$ -	$ 2,115	$ -	$ 2,215	-	-	-	10	-	-	-	$ -	$ 200	$ -	$ -	$ -	$ 200	$ 1,824	$ 23	$ 414	$ -	$ 156	$ 4,832
2021	Maint Dewater	-	-	-	45	-	-	$ -	$ -	$ 1,868	$ -	$ -	$ 1,868	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 24	$ 457	$ -	$ 156	$ 4,329
2022	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 23	$ 448	$ -	$ 156	$ 2,451
2023	-	-	-	3	-	-	-	$ -	$ 60	$ -	$ -	$ -	$ 60	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 29	$ 573	$ -	$ 156	$ 2,642
2024	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 30	$ 588	$ -	$ 156	$ 2,598
2025	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 28	$ 601	$ -	$ 156	$ 2,609
2026	Inspection	-	-	-	15	-	-	$ -	$ -	$ 525	$ -	$ -	$ 525	Inspection	-	-	1	15	-	-	$ -	$ 20	$ 525	$ -	$ -	$ 545	$ 1,824	$ 24	$ 552	$ -	$ 156	$ 3,626
2027	-	-	-	1	-	-	-	$ -	$ 20	$ -	$ -	$ -	$ 20	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 28	$ 612	$ -	$ 156	$ 2,640
2028	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 30	$ 807	$ -	$ 156	$ 2,817
2029	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	Hydraulic Failure	-	90	-	-	-	-	$ 3,803	$ -	$ -	$ -	$ -	$ 3,803	$ 1,824	$ 29	$ 727	$ -	$ 156	$ 6,539
2030	-	-	-	5	-	-	-	$ -	$ 100	$ -	$ -	$ -	$ 100	Hydr. System	-	-	-	-	45	-	$ -	$ -	$ -	$ 1,142	$ -	$ 1,142	$ 1,824	$ 14	$ 714	$ -	$ 156	$ 3,950
2031	Inspection	-	-	-	15	-	-	$ -	$ -	$ 525	$ -	$ -	$ 525	Elec Failure	-	90	-	-	-	-	$ 4,575	$ -	$ -	$ -	$ -	$ 4,575	$ 1,824	$ 19	$ 977	$ -	$ 156	$ 8,076
2032	CV Failure	-	10	-	-	-	-	$ 300	$ -	$ -	$ -	$ -	$ 300	Elec. System	-	-	3	-	30	-	$ -	$ 60	$ -	$ 2,500	$ -	$ 2,560	$ 1,824	$ 17	$ 955	$ -	$ 156	$ 5,812
2033	CV Replace	90	-	-	-	-	-	$ -	$ -	$ -	$ 2,800	$ -	$ 2,800	Maint. Dewater	-	-	-	45	-	-	$ -	$ -	$ 1,868	$ -	$ -	$ 1,868	$ 1,824	$ 18	$ 978	$ -	$ 156	$ 7,644
2034	-	-	-	1	-	-	-	$ -	$ 20	$ -	$ -	$ -	$ 20	Mgate Paint	-	-	-	45	-	-	$ -	$ -	$ 2,100	$ -	$ -	$ 2,100	$ 1,824	$ 15	$ 803	$ -	$ 156	$ 4,918
2035	Mgate Paint	-	-	-	45	-	-	$ -	$ -	$ 2,100	$ -	$ -	$ 2,100	CV Failure	-	30	-	-	-	-	$ 300	$ -	$ -	$ -	$ -	$ 300	$ 1,824	$ 17	$ 1,098	$ -	$ 156	$ 5,495
2036	Maint. Dewater	-	-	-	45	-	-	$ -	$ -	$ 1,868	$ -	$ -	$ 1,868	CV Replace	-	-	-	-	-	-	$ -	$ -	$ -	$ 1,400	$ -	$ 1,400	$ 1,824	$ 18	$ 1,134	$ -	$ 156	$ 6,400
2037	-	-	-	10	-	-	-	$ -	$ 200	$ -	$ -	$ -	$ 200	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 21	$ 1,536	$ -	$ 156	$ 3,737
2038	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	5	-	-	-	$ -	$ 100	$ -	$ -	$ -	$ 100	$ 1,824	$ 19	$ 1,411	$ -	$ 156	$ 3,510
2039	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 20	$ 1,477	$ -	$ 156	$ 3,477
2040	-	-	-	3	-	-	-	$ -	$ 60	$ -	$ -	$ -	$ 60	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 19	$ 1,660	$ -	$ 156	$ 3,719
2041	Inspection	-	-	-	15	-	-	$ -	$ -	$ 525	$ -	$ -	$ 525	Inspection	-	-	-	15	-	-	$ -	$ -	$ 525	$ -	$ -	$ 525	$ 1,824	$ 18	$ 1,617	$ -	$ 156	$ 4,665
2042	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 21	$ 1,987	$ -	$ 156	$ 3,988
2043	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 20	$ 2,258	$ -	$ 156	$ 4,258
2044	-	-	-	10	-	-	-	$ -	$ 200	$ -	$ -	$ -	$ 200	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 20	$ 2,222	$ -	$ 156	$ 4,422
2045	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	5	-	-	-	$ -	$ 100	$ -	$ -	$ -	$ 100	$ 1,824	$ 21	$ 2,459	$ -	$ 156	$ 4,560
2046	Inspection	-	-	-	15	-	-	$ -	$ -	$ 525	$ -	$ -	$ 525	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 22	$ 2,920	$ -	$ 156	$ 5,447
2047	-	-	-	5	-	-	-	$ -	$ 100	$ -	$ -	$ -	$ 100	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 23	$ 3,129	$ -	$ 156	$ 5,232
2048	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	Maint. Dewater	-	-	-	45	-	-	$ -	$ -	$ 1,868	$ -	$ -	$ 1,868	$ 1,824	$ 23	$ 3,271	$ -	$ 156	$ 7,142
2049	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 24	$ 3,775	$ -	$ 156	$ 5,779
2050	-	-	-	1	-	-	-	$ -	$ 20	$ -	$ -	$ -	$ 20	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 25	$ 4,477	$ 8,250	$ 156	$ 14,752
2051	Maint. Dewater	-	-	-	45	-	-	$ -	$ -	$ 1,868	$ -	$ -	$ 1,868	-	-	-	1	-	-	-	$ -	$ 20	$ -	$ -	$ -	$ 20	$ 1,824	$ 22	$ 3,990	$ 8,250	$ 156	$ 16,130
2052	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 27	$ 5,829	$ 8,250	$ 156	$ 16,086
2053	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 30	$ 6,160	$ 2,750	$ 156	$ 10,920
2054	-	-	-	3	-	-	-	$ -	$ 60	$ -	$ -	$ -	$ 60	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 42	$ 9,243	$ -	$ 156	$ 11,325
2055	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	Inspection	-	-	-	15	-	-	$ -	$ -	$ 525	$ -	$ -	$ 525	$ 1,824	$ 36	$ 9,335	$ -	$ 156	$ 11,876
2056	Inspection	-	-	-	15	-	-	$ -	$ -	$ 525	$ -	$ -	$ 525	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 44	$ 11,560	$ -	$ 156	$ 14,109
2057	-	-	-	3	-	-	-	$ -	$ 60	$ -	$ -	$ -	$ 60	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 55	$ 14,054	$ -	$ 156	$ 16,149
2058	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	10	-	-	-	$ -	$ 200	$ -	$ -	$ -	$ 200	$ 1,824	$ 55	$ 17,036	$ -	$ 156	$ 19,271
2059	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 60	$ 18,532	$ -	$ 156	$ 20,572
2060	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ -	$ -	$ -	$ 156	$ 1,980

TABLE 7-2. Most Likely Maintenance & Major Rehab Scenario (Without Project Condition) Closures & Costs (thousands of 1999$) --

			Main Closure Days					Main Chamber Costs								Auxiliary Closure Days					Auxiliary Chamber Costs						Other Project Costs					
			Unsch. Closures		Scheduled Closures			Unsch. Closures		Scheduled Closures						Uncsch. Closures		Scheduled Closures			Unsch. Closures		Scheduled Closures				Annual	LCLM Costs				
Year	Main. Item	F/E 1/2-speed	Unsch. Main.	Random Minor	Cyc. Main.	Comp. Repl.	Major Rehab.	Unsch. Main.	Random Minor	Cyc. Main.	Comp. Repl.	Major Rehab.	Total Costs	Main. Item	F/E 1/2-speed	Unsch. Main.	Random Minor	Cyc. Main.	Comp. Repl.	Major Rehab.	Unsch. Main.	Random Minor	Cyc. Main.	Comp. Repl.	Major Rehab.	Total Costs	O&M Costs	Repair	Trans. Delay	Dam Cost	Dredge Costs	Total Costs
2000	Inspection	-	-	-	15	-	-	$ 0	$ 0	$ 525	$ 0	$ 0	$ 525	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 46	$ 437	$ -	$ 156	$ 2,988
2001	-	-	-	-	-	-	-	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	-	-	-	5	-	-	-	$ -	$ 100	$ -	$ -	$ -	$ 100	$ 1,824	$ 53	$ 513	$ -	$ 156	$ 2,646
2002	-	-	-	5	-	-	-	$ 0	$ 100	$ 0	$ 0	$ 0	$ 100	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 49	$ 495	$ -	$ 156	$ 2,624
2003	-	-	-	-	-	-	-	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	Maint. Dewater	-	-	-	45	-	-	$ -	$ -	$ 1,868	$ -	$ -	$ 1,868	$ 1,824	$ 52	$ 571	$ -	$ 156	$ 4,471
2004	-	-	-	-	-	-	-	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	MG Paint	-	-	-	45	-	-	$ -	$ -	$ 2,100	$ -	$ -	$ 2,100	$ 1,824	$ 56	$ 613	$ -	$ 156	$ 4,749
2005	-	-	-	-	-	-	-	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 61	$ 676	$ -	$ 156	$ 2,717
2006	Maint. Dewater/Appr. W	-	-	-	60	-	-	$ 0	$ 0	$ 2,490	$ 0	$ 0	$ 2,490	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 60	$ 675	$ -	$ 156	$ 5,205
2007	MG Repair and Paint	-	-	-	60	-	-	$ 0	$ 0	$ 2,100	$ 0	$ 0	$ 2,100	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 64	$ 804	$ -	$ 156	$ 4,948
2008	-	-	-	-	-	-	-	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 63	$ 859	$ -	$ 156	$ 2,902
2009	-	-	-	-	-	-	-	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 65	$ 954	$ -	$ 156	$ 2,999
2010	-	-	-	10	-	-	-	$ 0	$ 200	$ 0	$ 0	$ 0	$ 200	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 69	$ 1,091	$ -	$ 156	$ 3,340
2011	Inspection	-	-	-	15	-	-	$ 0	$ 0	$ 525	$ 0	$ 0	$ 525	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 64	$ 955	$ -	$ 156	$ 3,524
2012	-	-	-	-	-	-	-	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	Inspection	-	-	-	15	-	-	$ -	$ -	$ 525	$ -	$ -	$ 525	$ 1,824	$ 73	$ 1,281	$ -	$ 156	$ 3,859
2013	-	-	-	1	-	-	-	$ 0	$ 20	$ 0	$ 0	$ 0	$ 20	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 74	$ 1,287	$ -	$ 156	$ 3,361
2014	-	-	-	-	-	-	-	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	-	-	-	1	-	-	-	$ -	$ 20	$ -	$ -	$ -	$ 20	$ 1,824	$ 78	$ 1,408	$ -	$ 156	$ 3,486
2015	-	-	-	-	-	-	-	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 81	$ 1,575	$ -	$ 156	$ 3,636
2016	Inspection	-	-	-	15	-	-	$ 0	$ 0	$ 525	$ 0	$ 0	$ 525	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 79	$ 1,622	$ -	$ 156	$ 4,206
2017	-	-	-	10	-	-	-	$ 0	$ 200	$ 0	$ 0	$ 0	$ 200	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 81	$ 1,712	$ -	$ 156	$ 3,973
2018	-	-	-	-	-	-	-	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 87	$ 1,862	$ -	$ 156	$ 3,929
2019	-	-	-	-	-	-	-	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	Maint Dewater	-	-	-	45	-	-	$ -	$ -	$ 1,868	$ -	$ -	$ 1,868	$ 1,824	$ 88	$ 2,048	$ -	$ 156	$ 5,984
2020	Hydr. System	-	-	5	-	60	-	$ 0	$ 100	$ 0	$ 2,115	$ 0	$ 2,215	-	-	-	10	-	-	-	$ -	$ 200	$ -	$ -	$ -	$ 200	$ 1,824	$ 23	$ 414	$ -	$ 156	$ 4,832
2021	Maint Dewater	-	-	-	45	-	-	$ 0	$ 0	$ 1,868	$ 0	$ 0	$ 1,868	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 24	$ 457	$ -	$ 156	$ 4,329
2022	-	-	-	-	-	-	-	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 23	$ 448	$ -	$ 156	$ 2,451
2023	-	-	-	3	-	-	-	$ 0	$ 60	$ 0	$ 0	$ 0	$ 60	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 29	$ 573	$ -	$ 156	$ 2,642
2024	-	-	-	-	-	-	-	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 30	$ 588	$ -	$ 156	$ 2,598
2025	-	-	-	-	-	-	-	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 28	$ 601	$ -	$ 156	$ 2,609
2026	Inspection	-	-	-	15	-	-	$ 0	$ 0	$ 525	$ 0	$ 0	$ 525	Inspection	-	-	1	15	-	-	$ -	$ 20	$ 525	$ -	$ -	$ 545	$ 1,824	$ 24	$ 552	$ -	$ 156	$ 3,626
2027	-	-	-	1	-	-	-	$ 0	$ 20	$ 0	$ 0	$ 0	$ 20	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 28	$ 612	$ -	$ 156	$ 2,640
2028	-	-	-	-	-	-	-	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 30	$ 807	$ -	$ 156	$ 2,817
2029	-	-	-	-	-	-	-	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 29	$ 727	$ -	$ 156	$ 2,736
2030	Culvert Valves	90	-	5	-	-	-	$ 0	$ 100	$ 0	$ 2,800	$ 0	$ 2,900	Hydr & Elec. Syste	-	-	-	-	60	-	$ -	$ -	$ -	$ 3,642	$ -	$ 3,642	$ 1,824	$ 14	$ 714	$ -	$ 156	$ 9,250
2031	Inspection	-	-	-	15	-	-	$ 0	$ 0	$ 525	$ 0	$ 0	$ 525	Culvert Valve	-	-	-	-	60	-	$ -	$ -	$ -	$ 1,400	$ -	$ 1,400	$ 1,824	$ 19	$ 977	$ -	$ 156	$ 4,901
2032	-	-	-	-	-	-	-	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	-	-	-	3	-	-	-	$ -	$ 60	$ -	$ -	$ -	$ 60	$ 1,824	$ 17	$ 955	$ -	$ 156	$ 3,012
2033	-	-	-	-	-	-	-	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	Maint. Dewater	-	-	-	45	-	-	$ -	$ -	$ 1,868	$ -	$ -	$ 1,868	$ 1,824	$ 18	$ 978	$ -	$ 156	$ 4,844
2034	-	-	-	1	-	-	-	$ 0	$ 20	$ 0	$ 0	$ 0	$ 20	Mgate Paint	-	-	-	45	-	-	$ -	$ -	$ 2,100	$ -	$ -	$ 2,100	$ 1,824	$ 15	$ 803	$ -	$ 156	$ 4,918
2035	Mgate Paint	-	-	-	45	-	-	$ 0	$ 0	$ 2,100	$ 0	$ 0	$ 2,100	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 17	$ 1,098	$ -	$ 156	$ 5,195
2036	Maint. Dewater	-	-	-	45	-	-	$ 0	$ 0	$ 1,868	$ 0	$ 0	$ 1,868	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 18	$ 1,134	$ -	$ 156	$ 5,000
2037	-	-	-	10	-	-	-	$ 0	$ 200	$ 0	$ 0	$ 0	$ 200	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 21	$ 1,536	$ -	$ 156	$ 3,737
2038	-	-	-	-	-	-	-	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	-	-	-	5	-	-	-	$ -	$ 100	$ -	$ -	$ -	$ 100	$ 1,824	$ 19	$ 1,411	$ -	$ 156	$ 3,510
2039	-	-	-	-	-	-	-	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 20	$ 1,477	$ -	$ 156	$ 3,477
2040	-	-	-	3	-	-	-	$ 0	$ 60	$ 0	$ 0	$ 0	$ 60	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 19	$ 1,660	$ -	$ 156	$ 3,719
2041	Inspection	-	-	-	15	-	-	$ 0	$ 0	$ 525	$ 0	$ 0	$ 525	Inspection	-	-	-	15	-	-	$ -	$ -	$ 525	$ -	$ -	$ 525	$ 1,824	$ 18	$ 1,617	$ -	$ 156	$ 4,665
2042	-	-	-	-	-	-	-	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 21	$ 1,987	$ -	$ 156	$ 3,988
2043	-	-	-	-	-	-	-	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 20	$ 2,258	$ -	$ 156	$ 4,258
2044	-	-	-	10	-	-	-	$ 0	$ 200	$ 0	$ 0	$ 0	$ 200	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 20	$ 2,222	$ -	$ 156	$ 4,422
2045	-	-	-	-	-	-	-	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	-	-	-	5	-	-	-	$ -	$ 100	$ -	$ -	$ -	$ 100	$ 1,824	$ 21	$ 2,459	$ -	$ 156	$ 4,560
2046	Inspection	-	-	-	15	-	-	$ 0	$ 0	$ 525	$ 0	$ 0	$ 525	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 22	$ 2,920	$ -	$ 156	$ 5,447
2047	-	-	-	5	-	-	-	$ 0	$ 100	$ 0	$ 0	$ 0	$ 100	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 23	$ 3,129	$ -	$ 156	$ 5,232
2048	-	-	-	-	-	-	-	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	Maint. Dewater	-	-	-	45	-	-	$ -	$ -	$ 1,868	$ -	$ -	$ 1,868	$ 1,824	$ 23	$ 3,271	$ -	$ 156	$ 7,142
2049	-	-	-	-	-	-	-	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 24	$ 3,775	$ -	$ 156	$ 5,779
2050	-	-	-	1	-	-	-	$ 0	$ 20	$ 0	$ 0	$ 0	$ 20	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 25	$ 4,477	$ 8,250	$ 156	$ 14,752
2051	Maint. Dewater	-	-	-	45	-	-	$ 0	$ 0	$ 1,868	$ 0	$ 0	$ 1,868	-	-	-	1	-	-	-	$ -	$ 20	$ -	$ -	$ -	$ 20	$ 1,824	$ 22	$ 3,990	$ 8,250	$ 156	$ 16,130
2052	-	-	-	-	-	-	-	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 27	$ 5,829	$ 8,250	$ 156	$ 16,086
2053	-	-	-	-	-	-	-	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 30	$ 6,160	$ 2,750	$ 156	$ 10,920
2054	-	-	-	3	-	-	-	$ 0	$ 60	$ 0	$ 0	$ 0	$ 60	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 42	$ 9,243	$ -	$ 156	$ 11,325
2055	-	-	-	-	-	-	-	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	Inspection	-	-	-	15	-	-	$ -	$ -	$ 525	$ -	$ -	$ 525	$ 1,824	$ 36	$ 9,335	$ -	$ 156	$ 11,876
2056	Inspection	-	-	-	15	-	-	$ 0	$ 0	$ 525	$ 0	$ 0	$ 525	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 44	$11,560	$ -	$ 156	$ 14,109
2057	-	-	-	3	-	-	-	$ 0	$ 60	$ 0	$ 0	$ 0	$ 60	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 55	$14,054	$ -	$ 156	$ 16,149
2058	-	-	-	-	-	-	-	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	-	-	-	10	-	-	-	$ -	$ 200	$ -	$ -	$ -	$ 200	$ 1,824	$ 55	$17,036	$ -	$ 156	$ 19,271
2059	-	-	-	-	-	-	-	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 60	$18,532	$ -	$ 156	$ 20,572
2060	-	-	-	-	-	-	-	$ 0	$ 0	$ 0	$ 0	$ 0	$ 0	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ -	$ -	$ -	$ 156	$ 1,980

TABLE 7-3. Baseline Scenario Closures & Costs (thousands of 1999$) -- Greenup

			Main Closure Days					Main Chamber Costs								Auxiliary Closure Days					Auxiliary Chamber Costs						Other Project Costs					
			Unsch. Closures		Scheduled Closures			Unsch. Closures		Scheduled Closures						Uncsch. Closures		Scheduled Closures			Unsch. Closures		Scheduled Closures				Annual	LCLM Costs				
Year	Main. Item	F/E 1/2-speed	Unsch. Main.	Random Minor	Cyc. Main.	Comp. Repl.	Major Rehab.	Unsch. Main.	Random Minor	Cyc. Main.	Comp. Repl.	Major Rehab.	Total Costs	Main. Item	F/E 1/2-speed	Unsch. Main.	Random Minor	Cyc. Main.	Comp. Repl.	Major Rehab.	Unsch. Main.	Random Minor	Cyc. Main.	Comp. Repl.	Major Rehab.	Total Costs	O&M Costs	Repair	Trans. Delay	Dam Cost	Dredge Costs	Total Costs
2000	-	-	-	10	-	-	-	$ -	$ 210	$ -	$ -	$ -	$ 210.00	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 44	$ 201	$ -	$ 133	$ 2,668
2001	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 45	$ 243	$ -	$ 133	$ 2,501
2002	MGate-S	-	-	-	15	-	-	$ -	$ -	$ 315	$ -	$ -	$ 315.00	-	-	-	10	-	-	-	$ -	$ 210	$ -	$ -	$ -	$ 210	$2,080	$ 52	$ 294	$ -	$ 133	$ 3,084
2003	MG Repair	-	-	10	45	-	-	$ -	$ 210	$ 1,238	$ -	$ -	$ 1,447.50	MGate-U	-	-	-	45	-	-	$ -	$ -	$ 1,238	$ -	$ -	$ 1,238	$2,080	$ 75	$ 576	$ -	$ 133	$ 5,549
2004	CValve-P	45	-	-	-	-	-	$ -	$ -	$ 990	$ -	$ -	$ 990.00	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 50	$ 310	$ -	$ 133	$ 3,563
2005	CValve-Q	45	-	-	-	-	-	$ -	$ -	$ 990	$ -	$ -	$ 990.00	-	-	-	3	-	-	-	$ -	$ 60	$ -	$ -	$ -	$ 60	$2,080	$ 46	$ 313	$ -	$ 133	$ 3,622
2006	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 49	$ 358	$ -	$ 133	$ 2,620
2007	MG Failure	-	90	-	-	-	-	$ 3,660	$ -	$ -	$ -	$ -	$ 3,660.00	CValve-R	-	-	-	45	-	-	$ -	$ -	$ 945	$ -	$ -	$ 945	$2,080	$ 51	$ 402	$ -	$ 133	$ 7,271
2008	Replace MG	-	-	-	-	90	-	$ -	$ -	$ -	$ 9,475	$ -	$ 9,475.00	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 50	$ 403	$ -	$ 133	$ 12,141
2009	Replace MG	-	-	-	-	60	-	$ -	$ -	$ -	$ 6,650	$ -	$ 6,650.00	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 56	$ 508	$ -	$ 133	$ 9,427
2010	-	-	-	3	-	-	-	$ -	$ 60	$ -	$ -	$ -	$ 60.00	MGate-V	-	-	-	45	-	-	$ -	$ -	$ 1,238	$ -	$ -	$ 1,238	$2,080	$ 54	$ 495	$ -	$ 133	$ 4,060
2011	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 56	$ 549	$ -	$ 133	$ 2,818
2012	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	10	-	-	-	$ -	$ 210	$ -	$ -	$ -	$ 210	$2,080	$ 57	$ 569	$ -	$ 133	$ 3,049
2013	-	-	-	5	-	-	-	$ -	$ 105	$ -	$ -	$ -	$ 105.00	MGate-T	-	-	-	15	-	-	$ -	$ -	$ 315	$ -	$ -	$ 315	$2,080	$ 57	$ 658	$ -	$ 133	$ 3,348
2014	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 58	$ 647	$ -	$ 133	$ 2,918
2015	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	3	-	-	-	$ -	$ 60	$ -	$ -	$ -	$ 60	$2,080	$ 60	$ 702	$ -	$ 133	$ 3,035
2016	-	-	-	10	-	-	-	$ -	$ 210	$ -	$ -	$ -	$ 210.00	-	-	-	10	-	-	-	$ -	$ 210	$ -	$ -	$ -	$ 210	$2,080	$ 57	$ 685	$ -	$ 133	$ 3,375
2017	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 61	$ 727	$ -	$ 133	$ 3,001
2018	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 57	$ 797	$ -	$ 133	$ 3,067
2019	MGate-S	-	-	-	15	-	-	$ -	$ -	$ 315	$ -	$ -	$ 315.00	-	-	-	10	-	-	-	$ -	$ 210	$ -	$ -	$ -	$ 210	$2,080	$ 60	$ 865	$ -	$ 133	$ 3,663
2020	MGate-U	-	-	-	45	-	-	$ -	$ -	$ 1,238	$ -	$ -	$ 1,237.50	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 64	$ 948	$ -	$ 133	$ 4,463
2021	CValve-P	45	-	-	-	-	-	$ -	$ -	$ 990	$ -	$ -	$ 990.00	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 62	$ 903	$ -	$ 133	$ 4,168
2022	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	10	-	-	-	$ -	$ 210	$ -	$ -	$ -	$ 210	$2,080	$ 66	$ 1,051	$ -	$ 133	$ 3,540
2023	CValve-Q	45	-	-	-	-	-	$ -	$ -	$ 990	$ -	$ -	$ 990.00	MGate-U	-	-	-	45	-	-	$ -	$ -	$ 1,238	$ -	$ -	$ 1,238	$2,080	$ 68	$ 1,029	$ -	$ 133	$ 5,538
2024	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 72	$ 1,173	$ -	$ 133	$ 3,458
2025	MGate-V	-	-	-	45	-	-	$ -	$ -	$ 1,238	$ -	$ -	$ 1,237.50	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 66	$ 1,117	$ -	$ 133	$ 4,634
2026	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 72	$ 1,208	$ -	$ 133	$ 3,493
2027	-	-	-	10	-	-	-	$ -	$ 210	$ -	$ -	$ -	$ 210.00	CValve-R	-	-	5	45	-	-	$ -	$ 105	$ 945	$ -	$ -	$ 1,050	$2,080	$ 69	$ 1,260	$ -	$ 133	$ 4,802
2028	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 73	$ 1,402	$ -	$ 133	$ 3,688
2029	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	MG Failure	-	90	-	-	-	-	$ 3,660	$ -	$ -	$ -	$ -	$ 3,660	$2,080	$ 70	$ 1,329	$ -	$ 133	$ 7,272
2030	-	-	-	10	-	-	-	$ -	$ 210	$ -	$ -	$ -	$ 210.00	Replace MG	-	-	-	-	90	-	$ -	$ -	$ -	$ 7,475	$ -	$ 7,475	$2,080	$ 72	$ 1,421	$ -	$ 133	$ 11,391
2031	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	Replace MG	-	-	-	-	60	-	$ -	$ -	$ -	$ 6,650	$ -	$ 6,650	$2,080	$ 75	$ 1,674	$ -	$ 133	$ 10,612
2032	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	Elec. Failure	-	90	-	-	-	-	$ 4,575	$ -	$ -	$ -	$ -	$ 4,575	$2,080	$ 78	$ 1,732	$ -	$ 133	$ 8,598
2033	MGate-S	-	-	-	15	-	-	$ -	$ -	$ 315	$ -	$ -	$ 315.00	Elec. Replace	-	-	-	-	30	-	$ -	$ -	$ -	$ 2,500	$ -	$ 2,500	$2,080	$ 79	$ 1,772	$ -	$ 133	$ 6,879
2034	MGate-U	-	-	-	45	-	-	$ -	$ -	$ 1,238	$ -	$ -	$ 1,237.50	MGate-T	-	-	-	15	-	-	$ -	$ -	$ 315	$ -	$ -	$ 315	$2,080	$ 77	$ 1,855	$ -	$ 133	$ 5,698
2035	CValve-P	45	-	-	-	-	-	$ -	$ -	$ 990	$ -	$ -	$ 990.00	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 75	$ 1,897	$ -	$ 133	$ 5,175
2036	CValve-Q	45	-	-	-	-	-	$ -	$ -	$ 990	$ -	$ -	$ 990.00	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 78	$ 2,123	$ -	$ 133	$ 5,404
2037	-	-	-	10	-	-	-	$ -	$ 210	$ -	$ -	$ -	$ 210.00	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 83	$ 2,316	$ -	$ 133	$ 4,822
2038	-	-	-	10	-	-	-	$ -	$ 210	$ -	$ -	$ -	$ 210.00	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 89	$ 2,678	$ -	$ 133	$ 5,190
2039	-	-	-	3	-	-	-	$ -	$ 60	$ -	$ -	$ -	$ 60.00	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 85	$ 2,607	$ -	$ 133	$ 4,965
2040	MGate-V	-	-	-	45	-	-	$ -	$ -	$ 1,238	$ -	$ -	$ 1,237.50	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 90	$ 2,969	$ -	$ 133	$ 6,510
2041	-	-	-	10	-	-	-	$ -	$ 210	$ -	$ -	$ -	$ 210.00	-	-	-	10	-	-	-	$ -	$ 210	$ -	$ -	$ -	$ 210	$2,080	$ 91	$ 3,329	$ -	$ 133	$ 6,053
2042	-	-	-	5	-	-	-	$ -	$ 105	$ -	$ -	$ -	$ 105.00	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 91	$ 3,243	$ -	$ 133	$ 5,652
2043	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 98	$ 3,602	$ 8,250	$ 133	$ 14,163
2044	-	-	-	10	-	-	-	$ -	$ 210	$ -	$ -	$ -	$ 210.00	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 95	$ 3,529	$ 8,250	$ 133	$ 14,297
2045	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 97	$ 3,875	$ 8,250	$ 133	$ 14,435
2046	-	-	-	3	-	-	-	$ -	$ 60	$ -	$ -	$ -	$ 60.00	-	-	-	10	-	-	-	$ -	$ 210	$ -	$ -	$ -	$ 210	$2,080	$ 99	$ 4,439	$ -	$ 133	$ 7,021
2047	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	CValve-R	-	-	-	45	-	-	$ -	$ -	$ 945	$ -	$ -	$ 945	$2,080	$ 100	$ 4,378	$ -	$ 133	$ 7,636
2048	-	-	-	10	-	-	-	$ -	$ 210	$ -	$ -	$ -	$ 210.00	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 101	$ 4,612	$ -	$ 133	$ 7,136
2049	MGate-S	-	-	-	15	-	-	$ -	$ -	$ 315	$ -	$ -	$ 315.00	MGate-U	-	-	-	45	-	-	$ -	$ -	$ 1,238	$ -	$ -	$ 1,238	$2,080	$ 102	$ 4,912	$ -	$ 133	$ 8,780
2050	MGate-U	-	-	-	45	-	-	$ -	$ -	$ 1,238	$ -	$ -	$ 1,237.50	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 101	$ 5,382	$ -	$ 133	$ 8,934
2051	CValve-P	45	-	-	-	-	-	$ -	$ -	$ 990	$ -	$ -	$ 990.00	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 105	$ 5,603	$ -	$ 133	$ 8,911
2052	CValve-Q	45	-	-	-	-	-	$ -	$ -	$ 990	$ -	$ -	$ 990.00	MGate-V	-	-	-	45	-	-	$ -	$ -	$ 1,238	$ -	$ -	$ 1,238	$2,080	$ 108	$ 6,580	$ -	$ 133	$ 11,129
2053	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 116	$ 7,398	$ -	$ 133	$ 9,727
2054	-	-	-	10	-	-	-	$ -	$ 210	$ -	$ -	$ -	$ 210.00	MGate-T	-	-	-	15	-	-	$ -	$ -	$ 315	$ -	$ -	$ 315	$2,080	$ 111	$ 7,673	$ -	$ 133	$ 10,522
2055	MGate-V	-	-	-	45	-	-	$ -	$ -	$ 1,238	$ -	$ -	$ 1,237.50	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 118	$ 9,158	$ -	$ 133	$ 12,727
2056	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	10	-	-	-	$ -	$ 210	$ -	$ -	$ -	$ 210	$2,080	$ 115	$ 9,779	$ -	$ 133	$ 12,317
2057	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 122	$ 10,700	$ -	$ 133	$ 13,035
2058	-	-	-	5	-	-	-	$ -	$ 105	$ -	$ -	$ -	$ 105.00	-	-	-	5	-	-	-	$ -	$ 105	$ -	$ -	$ -	$ 105	$2,080	$ 125	$ 12,251	$ -	$ 133	$ 14,799
2059	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 125	$ 12,634	$ -	$ 133	$ 14,972
2060	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ -	$ -	$ -	$ 133	$ 2,213

TABLE 7-4. Most Likely Maintenance & Major Rehab Scenario (Without Project Conditn.) Closures & Costs (thousands of 1999$) -- Gre

			Main Closure Days					Main Chamber Costs								Auxiliary Closure Days					Auxiliary Chamber Costs						Other Project Costs					
			Unsch. Closures		Scheduled Closures			Unsch. Closures		Scheduled Closures						Uncsch. Closures		Scheduled Closures			Unsch. Closures		Scheduled Closures				Annual	LCLM Costs				
Year	Main. Item	F/E 1/2-speed	Unsch. Main.	Random Minor	Cyc. Main.	Comp. Repl.	Major Rehab.	Unsch. Main.	Random Minor	Cyc. Main.	Comp. Repl.	Major Rehab.	Total Costs	Main. Item	F/E 1/2-speed	Unsch. Main.	Random Minor	Cyc. Main.	Comp. Repl.	Major Rehab.	Unsch. Main.	Random Minor	Cyc. Main.	Comp. Repl.	Major Rehab.	Total Costs	O&M Costs	Repair	Trans. Delay	Dam Cost	Dredge Costs	**Total Costs**
2000	-	-	-	10	-	-	-	$ -	$ 210	$ -	$ -	$ -	$ 210.00	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 44	$ 201	$ -	$ 133	$ 2,668
2001	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 45	$ 243	$ -	$ 133	$ 2,501
2002	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	10	-	-	-	$ -	$ 210	$ -	$ -	$ -	$ 210	$2,080	$ 52	$ 294	$ -	$ 133	$ 2,769
2003	MGate-S	-	-	10	15	-	-	$ -	$ 210	$ 315	$ -	$ -	$ 525.00	MGate-U	-	-	-	45	-	-	$ -	$ -	$ 1,238	$ -	$ -	$ 1,238	$2,080	$ 75	$ 576	$ -	$ 133	$ 4,627
2004	SMR (MG, EG)	-	-	-	-	-	90	$ -	$ -	$ -	$ -	$ 12,975	#########	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 50	$ 310	$ -	$ 133	$ 15,548
2005	SMR (MG Only)	-	-	-	-	-	60	$ -	$ -	$ -	$ -	$ 6,150	$ 6,150.00	SMR (EG)	-	-	3	-	-	90	$ -	$ 60	$ -	$ -	$ 6,475	$ 6,535	$2,080	$ 46	$ 313	$ -	$ 133	$ 15,257
2006	CValve-P	45	-	-	-	-	-	$ -	$ -	$ 990	$ -	$ -	$ 990.00	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 49	$ 358	$ -	$ 133	$ 3,610
2007	CValve-Q	45	-	-	-	-	-	$ -	$ -	$ 990	$ -	$ -	$ 990.00	CValve-R	-	-	-	45	-	-	$ -	$ -	$ 945	$ -	$ -	$ 945	$2,080	$ 51	$ 402	$ -	$ 133	$ 4,601
2008	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 50	$ 403	$ -	$ 133	$ 2,666
2009	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 56	$ 508	$ -	$ 133	$ 2,777
2010	-	-	-	3	-	-	-	$ -	$ 60	$ -	$ -	$ -	$ 60.00	MGate-V	-	-	-	45	-	-	$ -	$ -	$ 1,238	$ -	$ -	$ 1,238	$2,080	$ 54	$ 495	$ -	$ 133	$ 4,060
2011	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 56	$ 549	$ -	$ 133	$ 2,818
2012	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	10	-	-	-	$ -	$ 210	$ -	$ -	$ -	$ 210	$2,080	$ 57	$ 569	$ -	$ 133	$ 3,049
2013	-	-	-	5	-	-	-	$ -	$ 105	$ -	$ -	$ -	$ 105.00	MGate-T	-	-	-	15	-	-	$ -	$ -	$ 315	$ -	$ -	$ 315	$2,080	$ 57	$ 658	$ -	$ 133	$ 3,348
2014	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 58	$ 647	$ -	$ 133	$ 2,918
2015	MGate-S	-	-	-	15	-	-	$ -	$ -	$ 315	$ -	$ -	$ 315.00	-	-	-	3	-	-	-	$ -	$ 60	$ -	$ -	$ -	$ 60	$2,080	$ 60	$ 702	$ -	$ 133	$ 3,350
2016	MGate-U	-	-	10	45	-	-	$ -	$ 210	$ 1,238	$ -	$ -	$ 1,447.50	-	-	-	10	-	-	-	$ -	$ 210	$ -	$ -	$ -	$ 210	$2,080	$ 57	$ 685	$ -	$ 133	$ 4,613
2017	CValve-P	45	-	-	-	-	-	$ -	$ -	$ 990	$ -	$ -	$ 990.00	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 61	$ 727	$ -	$ 133	$ 3,991
2018	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 57	$ 797	$ -	$ 133	$ 3,067
2019	CValve-Q	45	-	-	-	-	-	$ -	$ -	$ 990	$ -	$ -	$ 990.00	-	-	-	10	-	-	-	$ -	$ 210	$ -	$ -	$ -	$ 210	$2,080	$ 60	$ 865	$ -	$ 133	$ 4,338
2020	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 64	$ 948	$ -	$ 133	$ 3,225
2021	MGate-V	-	-	-	45	-	-	$ -	$ -	$ 1,238	$ -	$ -	$ 1,237.50	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 62	$ 903	$ -	$ 133	$ 4,416
2022	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	10	-	-	-	$ -	$ 210	$ -	$ -	$ -	$ 210	$2,080	$ 66	$ 1,051	$ -	$ 133	$ 3,540
2023	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	MGate-U	-	-	-	45	-	-	$ -	$ -	$ 1,238	$ -	$ -	$ 1,238	$2,080	$ 68	$ 1,029	$ -	$ 133	$ 4,548
2024	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 72	$ 1,173	$ -	$ 133	$ 3,458
2025	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 66	$ 1,117	$ -	$ 133	$ 3,396
2026	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 72	$ 1,208	$ -	$ 133	$ 3,493
2027	-	-	-	10	-	-	-	$ -	$ 210	$ -	$ -	$ -	$ 210.00	CValve-R	-	-	5	45	-	-	$ -	$ 105	$ 945	$ -	$ -	$ 1,050	$2,080	$ 69	$ 1,260	$ -	$ 133	$ 4,802
2028	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 73	$ 1,402	$ -	$ 133	$ 3,688
2029	MGate-S	-	-	-	15	-	-	$ -	$ -	$ 315	$ -	$ -	$ 315.00	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 70	$ 1,329	$ -	$ 133	$ 3,927
2030	MGate-U	-	-	10	45	-	-	$ -	$ 210	$ 1,238	$ -	$ -	$ 1,447.50	SMR (MG, Elec)	-	-	-	-	-	60	$ -	$ -	$ -	$ -	$ 9,475	$ 9,475	$2,080	$ 72	$ 1,421	$ -	$ 133	$ 14,629
2031	CValve-P	45	-	-	-	-	-	$ -	$ -	$ 990	$ -	$ -	$ 990.00	SMR (MG Only)	-	-	10	-	-	60	$ -	$ 210	$ -	$ -	$ 6,150	$ 6,360	$2,080	$ 75	$ 1,674	$ -	$ 133	$ 11,312
2032	CValve-Q	45	-	-	-	-	-	$ -	$ -	$ 990	$ -	$ -	$ 990.00	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 78	$ 1,732	$ -	$ 133	$ 5,013
2033	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	MGate-T	-	-	-	15	-	-	$ -	$ -	$ 315	$ -	$ -	$ 315	$2,080	$ 79	$ 1,772	$ -	$ 133	$ 4,379
2034	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 77	$ 1,855	$ -	$ 133	$ 4,145
2035	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 75	$ 1,897	$ -	$ 133	$ 4,185
2036	MGate-V	-	-	-	45	-	-	$ -	$ -	$ 1,238	$ -	$ -	$ 1,237.50	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 78	$ 2,123	$ -	$ 133	$ 5,652
2037	-	-	-	10	-	-	-	$ -	$ 210	$ -	$ -	$ -	$ 210.00	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 83	$ 2,316	$ -	$ 133	$ 4,822
2038	-	-	-	10	-	-	-	$ -	$ 210	$ -	$ -	$ -	$ 210.00	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 89	$ 2,678	$ -	$ 133	$ 5,190
2039	-	-	-	3	-	-	-	$ -	$ 60	$ -	$ -	$ -	$ 60.00	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 85	$ 2,607	$ -	$ 133	$ 4,965
2040	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 90	$ 2,969	$ -	$ 133	$ 5,272
2041	-	-	-	10	-	-	-	$ -	$ 210	$ -	$ -	$ -	$ 210.00	-	-	-	10	-	-	-	$ -	$ 210	$ -	$ -	$ -	$ 210	$2,080	$ 91	$ 3,329	$ -	$ 133	$ 6,053
2042	-	-	-	5	-	-	-	$ -	$ 105	$ -	$ -	$ -	$ 105.00	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 91	$ 3,243	$ -	$ 133	$ 5,652
2043	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 98	$ 3,602	$ 8,250	$ 133	$ 14,163
2044	-	-	-	10	-	-	-	$ -	$ 210	$ -	$ -	$ -	$ 210.00	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 95	$ 3,529	$ 8,250	$ 133	$ 14,297
2045	MGate-S	-	-	-	15	-	-	$ -	$ -	$ 315	$ -	$ -	$ 315.00	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 97	$ 3,875	$ 8,250	$ 133	$ 14,750
2046	MGate-U	-	-	3	45	-	-	$ -	$ 60	$ 1,238	$ -	$ -	$ 1,297.50	-	-	-	10	-	-	-	$ -	$ 210	$ -	$ -	$ -	$ 210	$2,080	$ 99	$ 4,439	$ -	$ 133	$ 8,259
2047	CValve-P	45	-	-	-	-	-	$ -	$ -	$ 990	$ -	$ -	$ 990.00	CValve-R	-	-	-	45	-	-	$ -	$ -	$ 945	$ -	$ -	$ 945	$2,080	$ 100	$ 4,378	$ -	$ 133	$ 8,626
2048	CValve-Q	45	-	10	-	-	-	$ -	$ 210	$ 990	$ -	$ -	$ 1,200.00	MGate-U	-	-	-	45	-	-	$ -	$ -	$ 1,238	$ -	$ -	$ 1,238	$2,080	$ 101	$ 4,612	$ -	$ 133	$ 9,364
2049	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 102	$ 4,912	$ -	$ 133	$ 7,227
2050	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 101	$ 5,382	$ -	$ 133	$ 7,696
2051	MGate-V	-	-	-	45	-	-	$ -	$ -	$ 1,238	$ -	$ -	$ 1,237.50	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 105	$ 5,603	$ -	$ 133	$ 9,159
2052	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	MGate-V	-	-	-	45	-	-	$ -	$ -	$ 1,238	$ -	$ -	$ 1,238	$2,080	$ 108	$ 6,580	$ -	$ 133	$ 10,139
2053	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 116	$ 7,398	$ -	$ 133	$ 9,727
2054	-	-	-	10	-	-	-	$ -	$ 210	$ -	$ -	$ -	$ 210.00	MGate-T	-	-	-	15	-	-	$ -	$ -	$ 315	$ -	$ -	$ 315	$2,080	$ 111	$ 7,673	$ -	$ 133	$ 10,522
2055	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 118	$ 9,158	$ -	$ 133	$ 11,489
2056	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	10	-	-	-	$ -	$ 210	$ -	$ -	$ -	$ 210	$2,080	$ 115	$ 9,779	$ -	$ 133	$ 12,317
2057	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 122	$ 10,700	$ -	$ 133	$ 13,035
2058	-	-	-	5	-	-	-	$ -	$ 105	$ -	$ -	$ -	$ 105.00	-	-	-	5	-	-	-	$ -	$ 105	$ -	$ -	$ -	$ 105	$2,080	$ 125	$ 12,251	$ -	$ 133	$ 14,799
2059	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ 125	$ 12,634	$ -	$ 133	$ 14,972
2060	MGate-S	-	-	-	15	-	-	$ -	$ -	$ 315	$ -	$ -	$ 315.00	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$2,080	$ -	$ -	$ -	$ 133	$ 2,528

TABLE 7-5. 600' Extension in 2008 (w/qgco) Closures & Costs (thousands of 1999$) -- J.T. Myers

			Main Closure Days					Main Chamber Costs								Auxiliary Closure Days					Auxiliary Chamber Costs						Other Project Costs					
			Unsch. Closures		Scheduled Closures			Unsch. Closures		Scheduled Closures						Uncsch. Closures		Scheduled Closures			Unsch. Closures		Scheduled Closures				Annual	LCLM Costs				
Year	Main. Item	F/E 1/2-speed	Unsch. Main.	Random Minor	Cyc. Main.	Comp. Repl.	Major Rehab.	Unsch. Main.	Random Minor	Cyc. Main.	Comp. Repl.	Major Rehab.	Total Costs	Main. Item	F/E 1/2-speed	Unsch. Main.	Random Minor	Cyc. Main.	Comp. Repl.	Major Rehab.	Unsch. Main.	Random Minor	Cyc. Main.	Comp. Repl.	Major Rehab.	Total Costs	O&M Costs	Repair	Trans. Delay	Dam Cost	Dredge Costs	Total Costs
2000	Inspection	-	-	-	15	-	-	$ -	$ -	$ 525	$ -	$ -	$ 525	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 46		$ 0	$ 156	$ 2,551
2001	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	3	-	-	-	$ -	$ 60	$ -	$ -	$ -	$ 60	$ 1,824	$ 53		$ 0	$ 156	$ 2,093
2002	-	-	-	5	-	-	-	$ -	$ 100	$ -	$ -	$ -	$ 100	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 49		$ 0	$ 156	$ 2,129
2003	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 52		$ 0	$ 156	$ 2,032
2004	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	Inspection	-	-	-	15	-	-	$ -	$ -	$ 525	$ -	$ -	$ 525	$ 1,824	$ 56		$ 0	$ 156	$ 2,561
2005	Inspection	-	-	-	15	-	-	$ -	$ -	$ 525	$ -	$ -	$ 525	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 61		$ 0	$ 156	$ 2,566
2006	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	Plan 3	-	-	-	-	(2)	-	$ -	$ -	$ -	$ -	#####	$83,000	$ 1,824	$ 60		$ 0	$ 156	$ 85,040
2007	-	-	-	5	-	-	-	$ -	$ 100	$ -	$ -	$ -	$ 100	Plan 3	MG 5 Pai	-	-	-	(1)	-	$ -	$ -	$ 3,050	$ -	#####	$86,050	$ 1,824	$ 64		$ 0	$ 156	$ 88,194
2008	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 63		$ 0	$ 156	$ 2,043
2009	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 65		$ 0	$ 156	$ 2,045
2010	MG Repair & App Wall	-	-	10	30	-	-	$ -	$ 200	$ 1,745	$ -	$ -	$ 1,945	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 69		$ 0	$ 156	$ 3,994
2011	MG 1 Paint	-	-	-	-	-	-	$ -	$ -	$ 1,650	$ -	$ -	$ 1,650	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 64		$ 0	$ 156	$ 3,694
2012	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 73		$ 0	$ 156	$ 2,053
2013	-	-	-	1	-	-	-	$ -	$ 20	$ -	$ -	$ -	$ 20	Mgate 1	-	-	-	30	-	-	$ -	$ -	$ 1,745	$ -	$ -	$ 1,745	$ 1,824	$ 74		$ 0	$ 156	$ 3,819
2014	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	MG 2 Paint	-	-	1	-	-	-	$ -	$ 20	$ 1,650	$ -	$ -	$ 1,670	$ 1,824	$ 78		$ 0	$ 156	$ 3,728
2015	Mgate 2	-	-	-	30	-	-	$ -	$ -	$ 1,745	$ -	$ -	$ 1,745	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 81		$ 0	$ 156	$ 3,806
2016	MG 3 Paint	-	-	-	-	-	-	$ -	$ -	$ 1,650	$ -	$ -	$ 1,650	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 79		$ 0	$ 156	$ 3,709
2017	-	-	-	10	-	-	-	$ -	$ 200	$ -	$ -	$ -	$ 200	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 81		$ 0	$ 156	$ 2,261
2018	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	Inspection	-	-	-	10	-	-	$ -	$ -	$ 415	$ -	$ -	$ 415	$ 1,824	$ 87		$ 0	$ 156	$ 2,482
2019	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 88		$ 0	$ 156	$ 2,068
2020	Inspection	-	-	5	10	-	-	$ -	$ 100	$ 415	$ -	$ -	$ 515	-	-	-	10	-	-	-	$ -	$ 200	$ -	$ -	$ -	$ 200	$ 1,824	$ 23		$ 0	$ 156	$ 2,718
2021	Hydr. System	-	-	-	-	60	-	$ -	$ -	$ -	$ 2,115	$ -	$ 2,115	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 24		$ 0	$ 156	$ 4,119
2022	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 23		$ 0	$ 156	$ 2,003
2023	-	-	-	3	-	-	-	$ -	$ 60	$ -	$ -	$ -	$ 60	Mgate 3	-	-	-	15	-	-	$ -	$ -	$ 623	$ -	$ -	$ 623	$ 1,824	$ 29		$ 0	$ 156	$ 2,692
2024	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	MG 4 Repair	-	-	-	-	-	-	$ -	$ -	$ 300	$ -	$ -	$ 300	$ 1,824	$ 30		$ 0	$ 156	$ 2,310
2025	Mgate 4	-	-	-	15	-	-	$ -	$ -	$ 623	$ -	$ -	$ 623	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 28		$ 0	$ 156	$ 2,631
2026	MG 5 Repair	-	-	-	-	-	-	$ -	$ -	$ 300	$ -	$ -	$ 300	-	-	-	1	-	-	-	$ -	$ 20	$ -	$ -	$ -	$ 20	$ 1,824	$ 24		$ 0	$ 156	$ 2,324
2027	-	-	-	1	-	-	-	$ -	$ 20	$ -	$ -	$ -	$ 20	Mgate 5	-	-	-	15	-	-	$ -	$ -	$ 623	$ -	$ -	$ 623	$ 1,824	$ 28		$ 0	$ 156	$ 2,651
2028	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	MG 1 Repair	-	-	-	-	-	-	$ -	$ -	$ 300	$ -	$ -	$ 300	$ 1,824	$ 30		$ 0	$ 156	$ 2,310
2029	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 29		$ 0	$ 156	$ 2,009
2030	Mgate 1	-	-	5	15	-	-	$ -	$ 100	$ 623	$ -	$ -	$ 723	Hydr & Elec Syster	-	-	-	-	60	-	$ -	$ -	$ -	#####	$ -	$ 3,642	$ 1,824	$ 14		$ 0	$ 156	$ 6,359
2031	MG 2 Repair	-	-	-	-	-	-	$ -	$ -	$ 300	$ -	$ -	$ 300	Culvert Valves	-	-	-	-	60	-	$ -	$ -	$ -	#####	$ -	$ 1,400	$ 1,824	$ 19		$ 0	$ 156	$ 3,699
2032	Culvert Valves	90	-	-	-	-	-	$ -	$ -	$ -	$ 2,800	$ -	$ 2,800	-	-	-	3	-	-	-	$ -	$ 60	$ -	$ -	$ -	$ 60	$ 1,824	$ 17		$ 0	$ 156	$ 4,857
2033	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 18		$ 0	$ 156	$ 1,998
2034	-	-	-	1	-	-	-	$ -	$ 20	$ -	$ -	$ -	$ 20	Inspection	-	-	-	10	-	-	$ -	$ -	$ 415	$ -	$ -	$ 415	$ 1,824	$ 15		$ 0	$ 156	$ 2,430
2035	Inspection	-	-	-	10	-	-	$ -	$ -	$ 415	$ -	$ -	$ 415	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 17		$ 0	$ 156	$ 2,412
2036	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 18		$ 0	$ 156	$ 1,998
2037	-	-	-	10	-	-	-	$ -	$ 200	$ -	$ -	$ -	$ 200	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 21		$ 0	$ 156	$ 2,201
2038	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	5	-	-	-	$ -	$ 100	$ -	$ -	$ -	$ 100	$ 1,824	$ 19		$ 0	$ 156	$ 2,099
2039	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	Mgate 2	-	-	-	15	-	-	$ -	$ -	$ 623	$ -	$ -	$ 623	$ 1,824	$ 20		$ 0	$ 156	$ 2,623
2040	-	-	-	3	-	-	-	$ -	$ 60	$ -	$ -	$ -	$ 60	MG 3 Paint	-	-	-	-	-	-	$ -	$ -	$ 1,050	$ -	$ -	$ 1,050	$ 1,824	$ 19		$ 0	$ 156	$ 3,109
2041	Mgate 3	-	-	-	15	-	-	$ -	$ -	$ 623	$ -	$ -	$ 623	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 18		$ 0	$ 156	$ 2,621
2042	MG 4 Paint	-	-	-	-	-	-	$ -	$ -	$ 1,050	$ -	$ -	$ 1,050	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 21		$ 0	$ 156	$ 3,051
2043	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 20		$ 0	$ 156	$ 2,000
2044	-	-	-	10	-	-	-	$ -	$ 200	$ -	$ -	$ -	$ 200	Mgate 4	-	-	-	15	-	-	$ -	$ -	$ 623	$ -	$ -	$ 623	$ 1,824	$ 20		$ 0	$ 156	$ 2,823
2045	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	MG 5 Paint	-	-	5	-	-	-	$ -	$ 100	$ 1,350	$ -	$ -	$ 1,450	$ 1,824	$ 21		$ 0	$ 156	$ 3,451
2046	Mgate 5	-	-	-	15	-	-	$ -	$ -	$ 623	$ -	$ -	$ 623	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 22		$ 0	$ 156	$ 2,625
2047	MG 1 Paint	-	-	5	-	-	-	$ -	$ 100	$ 1,350	$ -	$ -	$ 1,450	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 23		$ 0	$ 156	$ 3,453
2048	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 23		$ 0	$ 156	$ 2,003
2049	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	Inspection	-	-	-	10	-	-	$ -	$ -	$ 415	$ -	$ -	$ 415	$ 1,824	$ 24		$ 0	$ 156	$ 2,419
2050	-	-	-	1	-	-	-	$ -	$ 20	$ -	$ -	$ -	$ 20	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 25		$ 8,250	$ 156	$ 10,275
2051	Inspection	-	-	-	10	-	-	$ -	$ -	$ 415	$ -	$ -	$ 415	-	-	-	1	-	-	-	$ -	$ 20	$ -	$ -	$ -	$ 20	$ 1,824	$ 22		$ 8,250	$ 156	$ 10,687
2052	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 27		$ 8,250	$ 156	$ 10,257
2053	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 30		$ 2,750	$ 156	$ 4,760
2054	-	-	-	3	-	-	-	$ -	$ 60	$ -	$ -	$ -	$ 60	Mgate 1	-	-	-	15	-	-	$ -	$ -	$ 623	$ -	$ -	$ 623	$ 1,824	$ 42		$ 0	$ 156	$ 2,705
2055	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	MG 2 Paint	-	-	-	-	-	-	$ -	$ -	$ 1,350	$ -	$ -	$ 1,350	$ 1,824	$ 36		$ 0	$ 156	$ 3,366
2056	Mgate 2	-	-	-	15	-	-	$ -	$ -	$ 623	$ -	$ -	$ 623	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 44		$ 0	$ 156	$ 2,647
2057	MG 3 Repair	-	-	3	-	-	-	$ -	$ 60	$ 300	$ -	$ -	$ 360	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 1,824	$ 55		$ 0	$ 156	$ 2,395
2058	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	10	-	-	-	$ -	$ 200	$ -	$ -	$ -	$ 200	$ 1,824	$ 55		$ 0	$ 156	$ 2,235
2059	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	Mgate 3	-	-	-	15	-	-	$ -	$ -	$ 623	$ -	$ -	$ 623	$ 1,824	$ 60		$ 0	$ 156	$ 2,663
2060	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	MG 4 Repair	-	-	-	-	-	-	$ -	$ -	$ 300	$ -	$ -	$ 300	$ 1,824	$ 0		$ 0	$ 156	$ 2,280

TABLE 7-6. 600' Extension in 2008 (w/qgco) Closures & Costs (thousands of 1999$) -- Greenup

			Main Closure Days					Main Chamber Costs								Auxiliary Closure Days					Auxiliary Chamber Costs						Other Project Costs					
			Unsch. Closures		Scheduled Closures			Unsch. Closures		Scheduled Closures						Uncsch. Closures		Scheduled Closures			Unsch. Closures		Scheduled Closures				Annual	LCLM Costs				
Year	Main. Item	F/E 1/2-speed	Unsch. Main.	Random Minor	Cyc. Main.	Comp. Repl.	Major Rehab.	Unsch. Main.	Random Minor	Cyc. Main.	Comp. Repl.	Major Rehab.	Total Costs	Main. Item	F/E 1/2-speed	Unsch. Main.	Random Minor	Cyc. Main.	Comp. Repl.	Major Rehab.	Unsch. Main.	Random Minor	Cyc. Main.	Comp. Repl.	Major Rehab.	Total Costs	O&M Costs	Repair	Trans. Delay	Dam Cost	Dredge Costs	Total Costs
2000	-	-	-	10	-	-	-	$ -	$ 210	$ -	$ -	$ -	$ 210	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 2,080	$ 44		$ -	$ 133	$ 2,467
2001	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 2,080	$ 45		$ -	$ 133	$ 2,258
2002	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	10	-	-	-	$ -	$ 210	$ -	$ -	$ -	$ 210	$ 2,080	$ 52		$ -	$ 133	$ 2,475
2003	MG Repair	-	-	10	45	-	-	$ -	$ 210	$ 1,238	$ -	$ -	$ 1,448	Mgate U	-	-	-	45	-	-	$ -	$ -	$ 945	$ -	$ -	$ 945	$ 2,080	$ 75		$ -	$ 133	$ 4,681
2004	CValve-P	45	-	-	-	-	-	$ -	$ -	$ 990	$ -	$ -	$ 990	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 2,080	$ 50		$ -	$ 133	$ 3,253
2005	CValve-Q	45	-	-	-	-	-	$ -	$ -	$ 990	$ -	$ -	$ 990	CValve-R	-	-	3	45	-	-	$ -	$ 60	$ 945	$ -	$ -	$ 1,005	$ 2,080	$ 46		$ -	$ 133	$ 4,254
2006	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	Plan 3 - 600' ext	-	-	-	-	(2)	-	$ -	$ -	$ -	$ 84,000	$ -	$ 84,000	$ 2,080	$ 49		$ -	$ 133	$ 86,262
2007	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	Plan 3 - 600' ext		-	-	-	(1)	-	$ -	$ -	$ -	$ 84,000	$ -	$ 84,000	$ 2,080	$ 51		$ -	$ 133	$ 86,264
2008	SMR (MG, EG)	-	-	-	-	-	90	$ -	$ -	$ -	$ -	$ 12,975	$ 12,975	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 2,080	$ 50		$ -	$ 133	$ 15,238
2009	SMR (MG)	-	-	3	-	-	60	$ -	$ 60	$ -	$ 6,475	$ 6,150	$ 12,685	SMR (EG)	-	-	-	-	-	90	$ -	$ -	$ -	$ 300	$ 6,475	$ 6,775	$ 2,080	$ 56		$ -	$ 133	$ 21,729
2010	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	MG 4 Paint	-	-	-	-	-	-	$ -	$ -	$ 1,650	$ -	$ -	$ 1,650	$ 2,080	$ 54		$ -	$ 133	$ 3,917
2011	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	MGate-T	-	-	-	15	-	-	$ -	$ -	$ 315	$ -	$ -	$ 315	$ 2,080	$ 56		$ -	$ 133	$ 2,584
2012	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	10	-	-	-	$ -	$ 210	$ -	$ -	$ -	$ 210	$ 2,080	$ 57		$ -	$ 133	$ 2,480
2013	-	-	-	5	-	-	-	$ -	$ 105	$ -	$ -	$ -	$ 105	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 2,080	$ 57		$ -	$ 133	$ 2,375
2014	MGate-S	-	-	-	15	-	-	$ -	$ -	$ 315	$ -	$ -	$ 315	Mgate Insp	-	-	-	10	-	-	$ -	$ -	$ 210	$ -	$ -	$ 210	$ 2,080	$ 58		$ -	$ 133	$ 2,796
2015	Mgate 4	-	-	-	15	-	-	$ -	$ -	$ 413	$ -	$ -	$ 413	-	-	-	3	-	-	-	$ -	$ 60	$ -	$ -	$ -	$ 60	$ 2,080	$ 60		$ -	$ 133	$ 2,746
2016	MG 6 Repair	-	-	10	-	-	-	$ -	$ 210	$ 300	$ -	$ -	$ 510	-	-	-	10	-	-	-	$ -	$ 210	$ -	$ -	$ -	$ 210	$ 2,080	$ 57		$ -	$ 133	$ 2,990
2017	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 2,080	$ 61		$ -	$ 133	$ 2,274
2018	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	Mgate 6	-	-	-	15	-	-	$ -	$ -	$ 315	$ -	$ -	$ 315	$ 2,080	$ 57		$ -	$ 133	$ 2,585
2019	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	MG 3 Repair	-	-	10	-	-	-	$ -	$ 210	$ 1,650	$ -	$ -	$ 1,860	$ 2,080	$ 60		$ -	$ 133	$ 4,133
2020	Mgate 3	-	-	-	15	-	-	$ -	$ -	$ 413	$ -	$ -	$ 413	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 2,080	$ 64		$ -	$ 133	$ 2,690
2021	MG 7 Repair	-	-	-	-	-	-	$ -	$ -	$ 300	$ -	$ -	$ 300	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 2,080	$ 62		$ -	$ 133	$ 2,575
2022	CValve-P	45	-	-	-	-	-	$ -	$ -	$ 990	$ -	$ -	$ 990	-	-	-	10	-	-	-	$ -	$ 210	$ -	$ -	$ -	$ 210	$ 2,080	$ 66		$ -	$ 133	$ 3,479
2023	CValve-Q	45	-	-	-	-	-	$ -	$ -	$ 990	$ -	$ -	$ 990	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 2,080	$ 68		$ -	$ 133	$ 3,271
2024	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	Mgate 7	-	-	-	15	-	-	$ -	$ -	$ 315	$ -	$ -	$ 315	$ 2,080	$ 72		$ -	$ 133	$ 2,600
2025	Mgate Insp	-	-	-	10	-	-	$ -	$ -	$ 210	$ -	$ -	$ 210	MG 5 Repair	-	-	-	-	-	-	$ -	$ -	$ 300	$ -	$ -	$ 300	$ 2,080	$ 66		$ -	$ 133	$ 2,789
2026	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 2,080	$ 72		$ -	$ 133	$ 2,285
2027	-	-	-	10	-	-	-	$ -	$ 210	$ -	$ -	$ -	$ 210	CValve-R	-	-	5	45	-	-	$ -	$ 105	$ 945	$ -	$ -	$ 1,050	$ 2,080	$ 69		$ -	$ 133	$ 3,542
2028	MGate-S	-	-	-	15	-	-	$ -	$ -	$ 315	$ -	$ -	$ 315	MGate-T	-	-	-	15	-	-	$ -	$ -	$ 315	$ -	$ -	$ 315	$ 2,080	$ 73		$ -	$ 133	$ 2,916
2029	Mgate 5	-	-	-	15	-	-	$ -	$ -	$ 413	$ -	$ -	$ 413	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 2,080	$ 70		$ -	$ 133	$ 2,696
2030	MG 4 Hold only	-	-	10	-	-	-	$ -	$ 210	$ -	$ -	$ -	$ 210	SMR (MG, Elec)	-	-	-	-	-	60	$ -	$ -	$ -	$ -	$ 8,975	$ 8,975	$ 2,080	$ 72		$ -	$ 133	$ 11,470
2031	Mgate 8	Scrap MG3	-	-	15	-	-	$ -	$ -	$ 413	$ -	$ -	$ 413	SMR (MG Only)	-	-	10	-	-	60	$ -	$ 210	$ -	$ -	$ 6,150	$ 6,360	$ 2,080	$ 75		$ -	$ 133	$ 9,061
2032	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	MG 6 Paint	-	-	-	-	-	-	$ -	$ -	$ 1,350	$ -	$ -	$ 1,350	$ 2,080	$ 78		$ -	$ 133	$ 3,641
2033	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 2,080	$ 79		$ -	$ 133	$ 2,292
2034	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 2,080	$ 77		$ -	$ 133	$ 2,290
2035	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 2,080	$ 75		$ -	$ 133	$ 2,288
2036	CValve-Q	45	-	-	-	-	-	$ -	$ -	$ 990	$ -	$ -	$ 990	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 2,080	$ 78		$ -	$ 133	$ 3,281
2037	Mgate Insp	-	-	10	10	-	-	$ -	$ 210	$ 210	$ -	$ -	$ 420	Mgate Insp	-	-	-	10	-	-	$ -	$ -	$ 210	$ -	$ -	$ 210	$ 2,080	$ 83		$ -	$ 133	$ 2,926
2038	CValve-P	45	-	10	-	-	-	$ -	$ -	$ 990	$ -	$ -	$ 990	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 2,080	$ 89		$ -	$ 133	$ 3,292
2039	-	-	-	3	-	-	-	$ -	$ 60	$ -	$ -	$ -	$ 60	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 2,080	$ 85		$ -	$ 133	$ 2,358
2040	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 2,080	$ 90		$ -	$ 133	$ 2,303
2041	-	-	-	10	-	-	-	$ -	$ 210	$ -	$ -	$ -	$ 210	-	-	-	10	-	-	-	$ -	$ 210	$ -	$ -	$ -	$ 210	$ 2,080	$ 91		$ -	$ 133	$ 2,724
2042	Mgate Insp	-	-	5	10	-	-	$ -	$ 105	$ 210	$ -	$ -	$ 315	Mgate 6	-	-	-	15	-	-	$ -	$ -	$ 315	$ -	$ -	$ 315	$ 2,080	$ 91		$ -	$ 133	$ 2,934
2043	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	MG 7 Paint	-	-	-	-	-	-	$ -	$ -	$ 1,350	$ -	$ -	$ 1,350	$ 2,080	$ 98		$ 8,250	$ 133	$ 11,911
2044	MGate-S	-	-	10	15	-	-	$ -	$ 210	$ 315	$ -	$ -	$ 525	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 2,080	$ 95		$ 8,250	$ 133	$ 11,083
2045	Mgate 7	-	-	-	15	-	-	$ -	$ -	$ 413	$ -	$ -	$ 413	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 2,080	$ 97		$ 8,250	$ 133	$ 10,973
2046	MG 5 Paint	-	-	3	-	-	-	$ -	$ 60	$ 1,350	$ -	$ -	$ 1,410	CValve-R	-	-	10	45	-	-	$ -	$ 210	$ 945	$ -	$ -	$ 1,155	$ 2,080	$ 99		$ -	$ 133	$ 4,877
2047	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	Mgate 5	-	-	-	15	-	-	$ -	$ -	$ 413	$ -	$ -	$ 413	$ 2,080	$ 100		$ -	$ 133	$ 2,726
2048	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	MG 9 Repair	-	-	-	-	-	-	$ -	$ -	$ 300	$ -	$ -	$ 300	$ 2,080	$ 101		$ -	$ 133	$ 2,614
2049	Mgate 9	-	-	-	15	-	-	$ -	$ -	$ 413	$ -	$ -	$ 413	MGate-T	-	-	-	15	-	-	$ -	$ -	$ 315	$ -	$ -	$ 315	$ 2,080	$ 102		$ -	$ 133	$ 3,043
2050	MG 8 Repair	-	-	-	-	-	-	$ -	$ -	$ 300	$ -	$ -	$ 300	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 2,080	$ 101		$ -	$ 133	$ 2,614
2051	-	-	-	10	-	-	-	$ -	$ 210	$ -	$ -	$ -	$ 210	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 2,080	$ 105		$ -	$ 133	$ 2,528
2052	CValve-Q	45	-	-	-	-	-	$ -	$ -	$ 990	$ -	$ -	$ 990	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 2,080	$ 108		$ -	$ 133	$ 3,311
2053	CValve-P	45	-	-	-	-	-	$ -	$ -	$ 990	$ -	$ -	$ 990	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 2,080	$ 116		$ -	$ 133	$ 3,319
2054	-	-	-	10	-	-	-	$ -	$ 210	$ -	$ -	$ -	$ 210	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 2,080	$ 111		$ -	$ 133	$ 2,534
2055	Mgate Insp	-	-	-	10	-	-	$ -	$ -	$ 210	$ -	$ -	$ 210	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 2,080	$ 118		$ -	$ 133	$ 2,541
2056	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	Mgate Insp	-	-	10	10	-	-	$ -	$ 210	$ 210	$ -	$ -	$ 420	$ 2,080	$ 115		$ -	$ 133	$ 2,748
2057	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 2,080	$ 122		$ -	$ 133	$ 2,335
2058	-	-	-	5	-	-	-	$ -	$ 105	$ -	$ -	$ -	$ 105	-	-	-	5	-	-	-	$ -	$ 105	$ -	$ -	$ -	$ 105	$ 2,080	$ 125		$ -	$ 133	$ 2,548
2059	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 2,080	$ 125		$ -	$ 133	$ 2,338
2060	Mgate 8	-	-	-	15	-	-	$ -	$ -	$ 413	$ -	$ -	$ 413	-	-	-	-	-	-	-	$ -	$ -	$ -	$ -	$ -	$ -	$ 2,080	$ -		$ -	$ 133	$ 2,626